

US009350272B2

(12) **United States Patent**  
**Sumioka et al.**

(10) **Patent No.:** **US 9,350,272 B2**  
(45) **Date of Patent:** **May 24, 2016**

(54) **DRIVING CIRCUIT FOR VIBRATION-TYPE ACTUATOR**

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(\*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 141 days.

(21) Appl. No.: **14/307,367**

(22) Filed: **Jun. 17, 2014**

(65) **Prior Publication Data**

US 2014/0292233 A1 Oct. 2, 2014

**Related U.S. Application Data**

(63) Continuation of application No. 14/017,089, filed on Sep. 3, 2013, now Pat. No. 8,791,622, which is a continuation of application No. 12/905,993, filed on Oct. 15, 2010, now Pat. No. 8,552,619.

(30) **Foreign Application Priority Data**

Nov. 20, 2009 (JP) ..... 2009-265234

(51) **Int. Cl.**  
**H01L 41/09** (2006.01)  
**H02N 2/00** (2006.01)

(52) **U.S. Cl.**  
CPC ..... **H02N 2/008** (2013.01)

(58) **Field of Classification Search**  
USPC ..... 310/316.01–316.03, 317–319  
See application file for complete search history.

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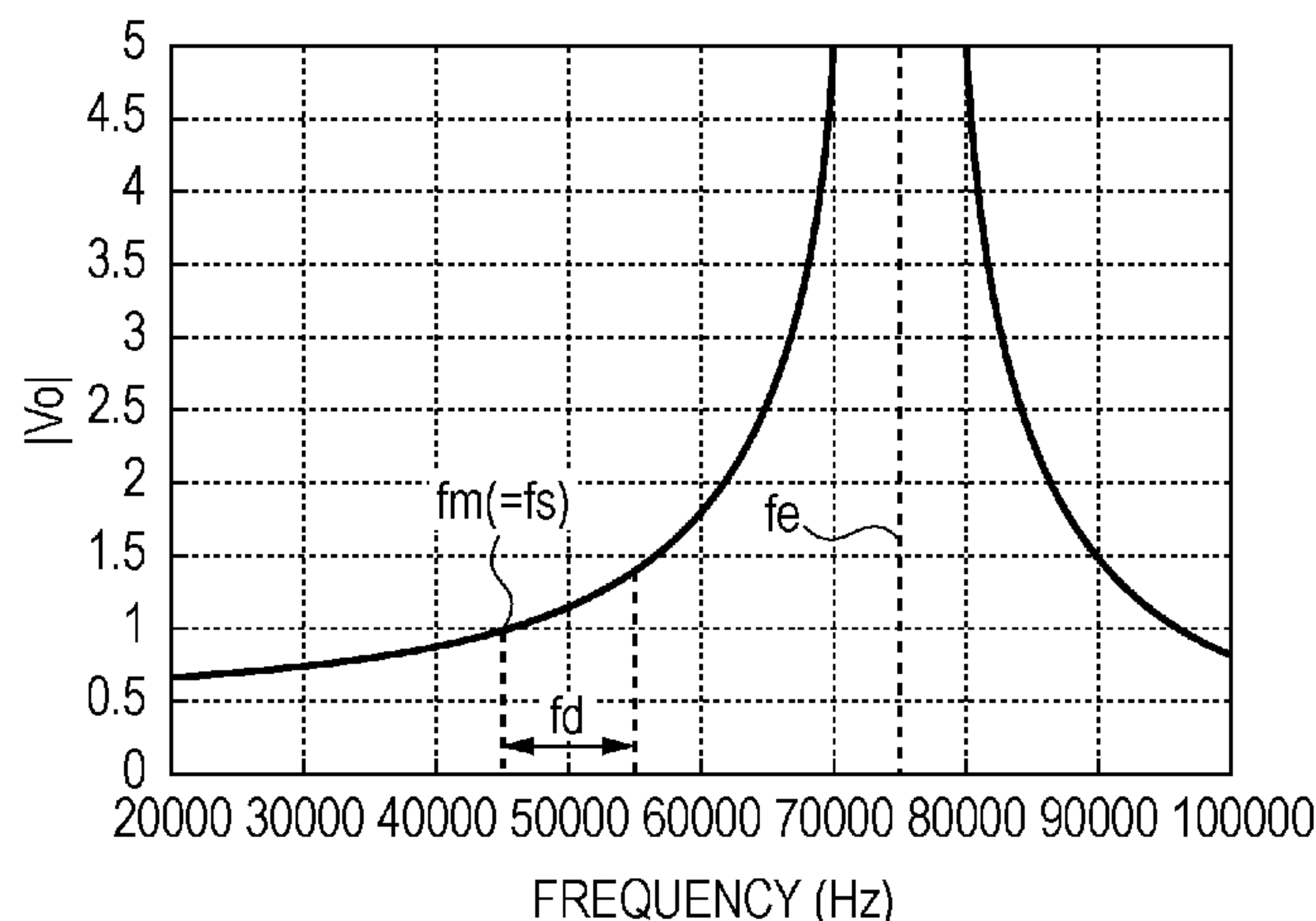
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(57) **ABSTRACT**

A driving circuit to drive a vibration member comprising an electro-mechanical energy conversion element includes a transformer connected in parallel to the electro-mechanical energy conversion element. The transformer includes a primary coil configured such that an alternating voltage is applied to the primary coil, and a secondary coil connected to the electro-mechanical energy conversion element in parallel, and an inductor connected to the primary coil in series. Parameters of the driving circuit are set such that, when a frequency of a peak voltage applied to the electro-mechanical energy conversion element is denoted by  $f_e$  and a driving frequency of the vibration member is denoted by  $f_d$ , a condition  $f_e < 1.5 \cdot f_d$  is satisfied.

**15 Claims, 13 Drawing Sheets**



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FIG. 1A

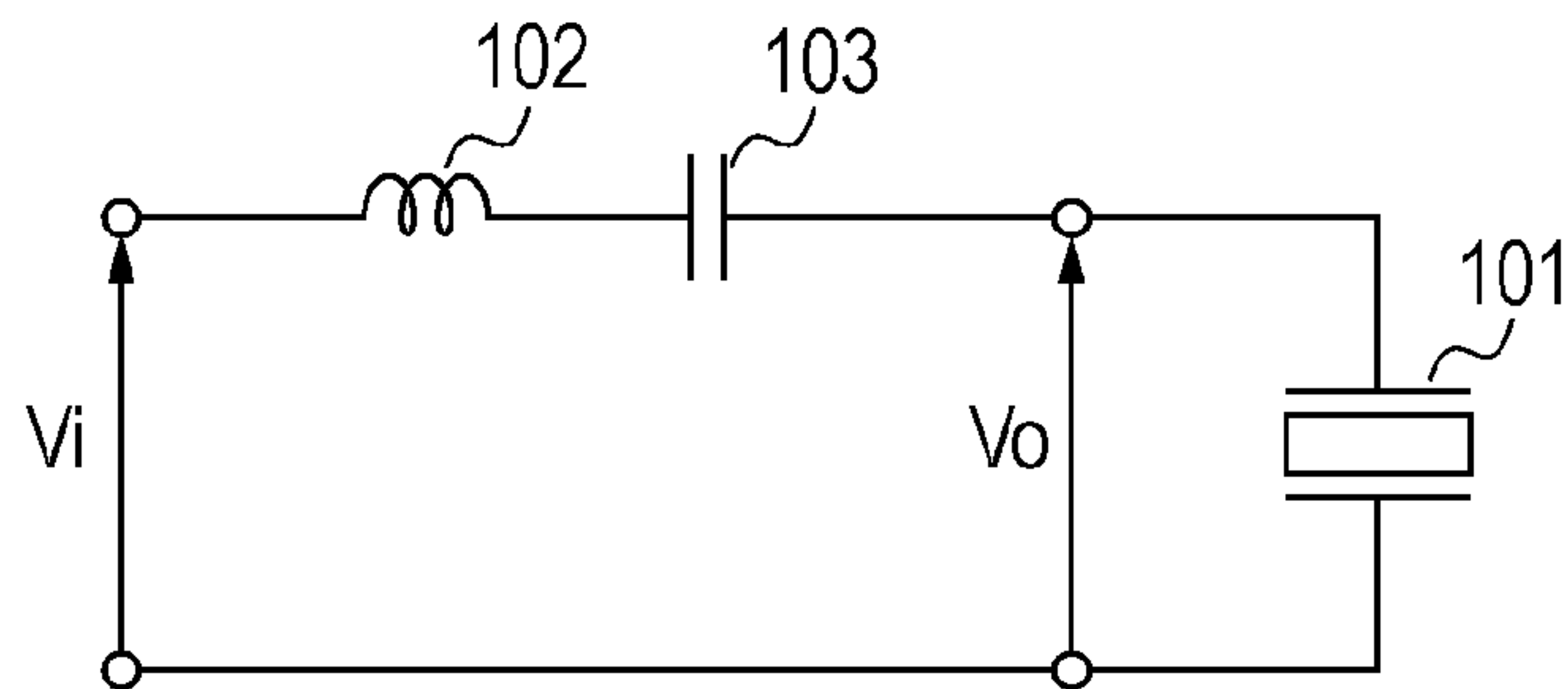


FIG. 1B

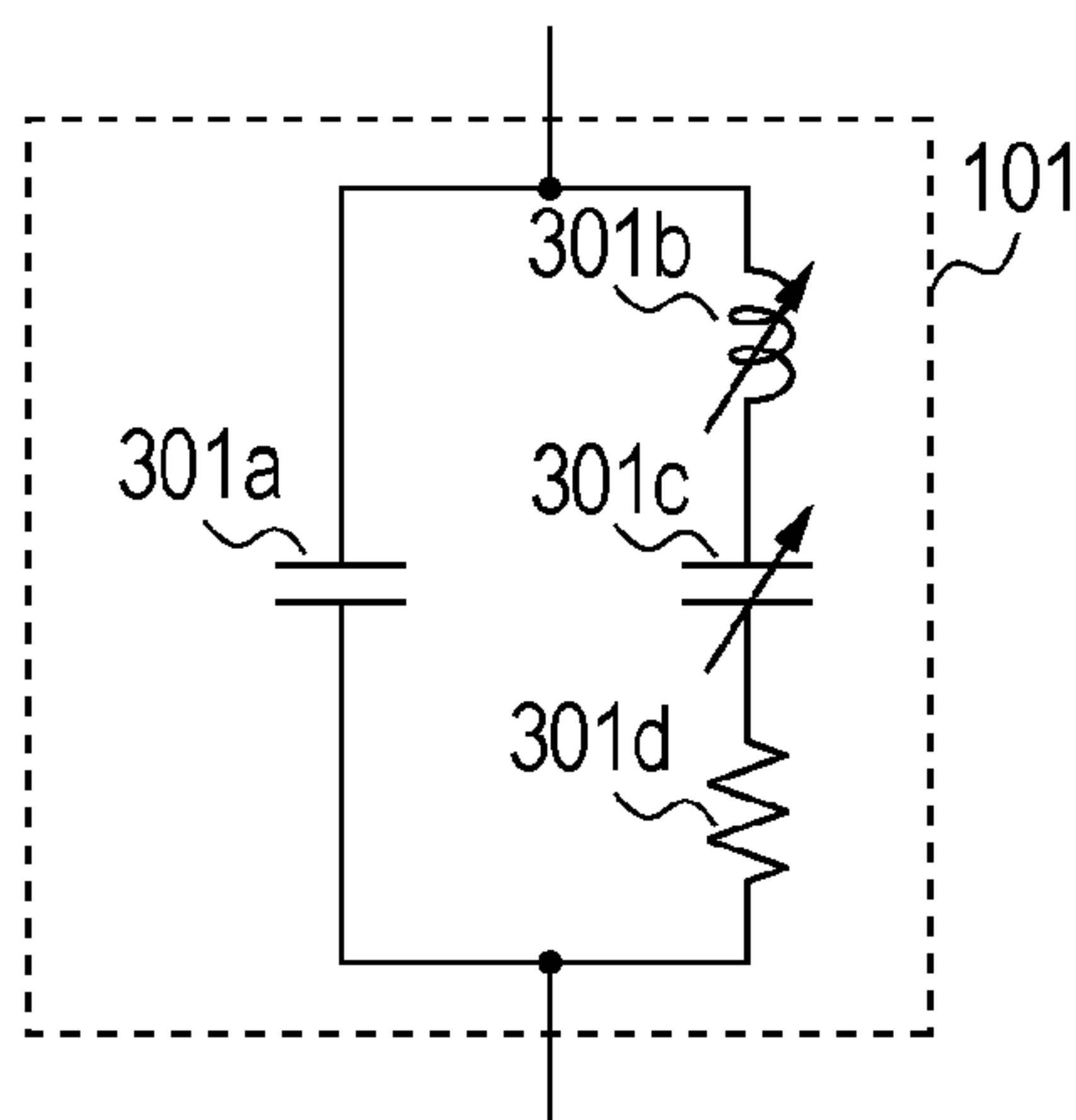


FIG. 1C

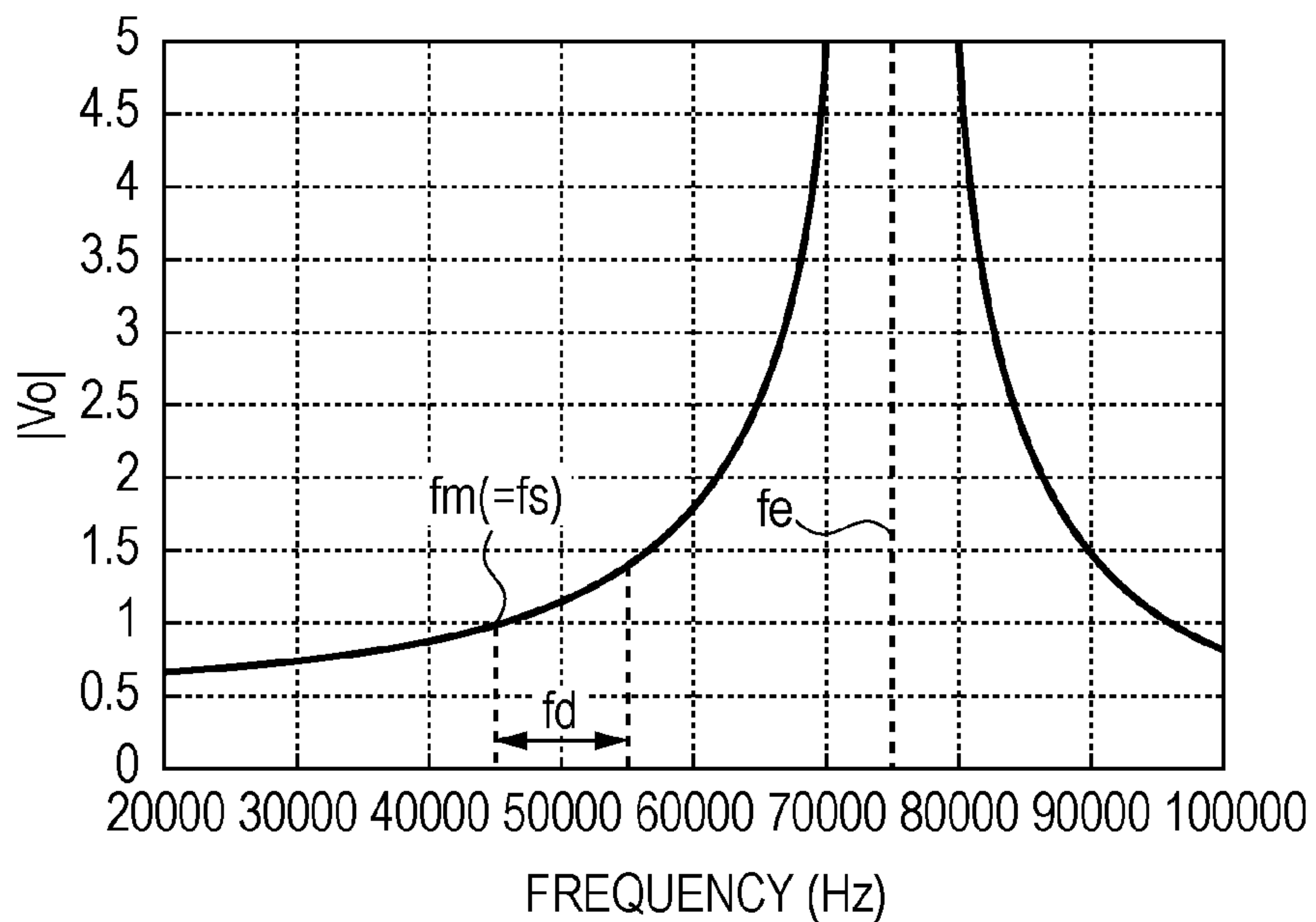


FIG. 2A

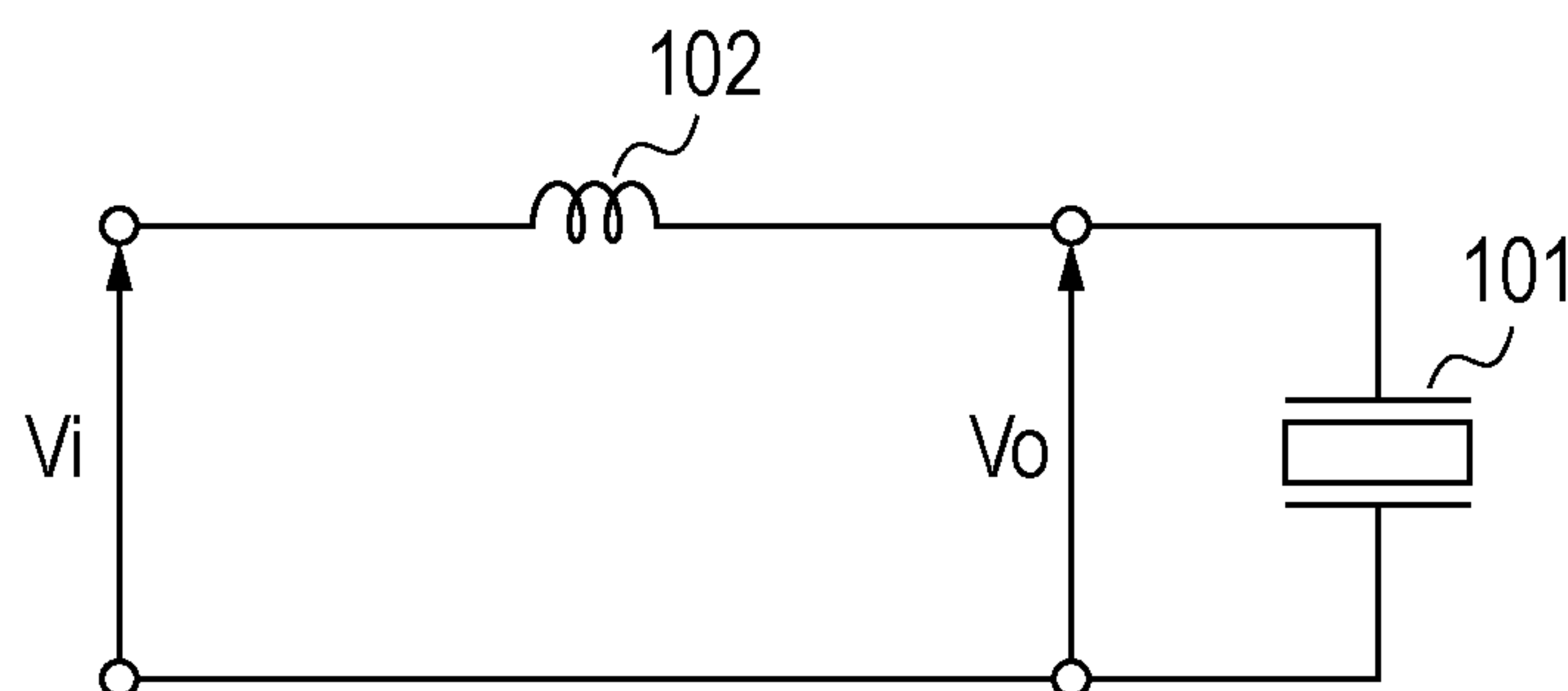


FIG. 2B

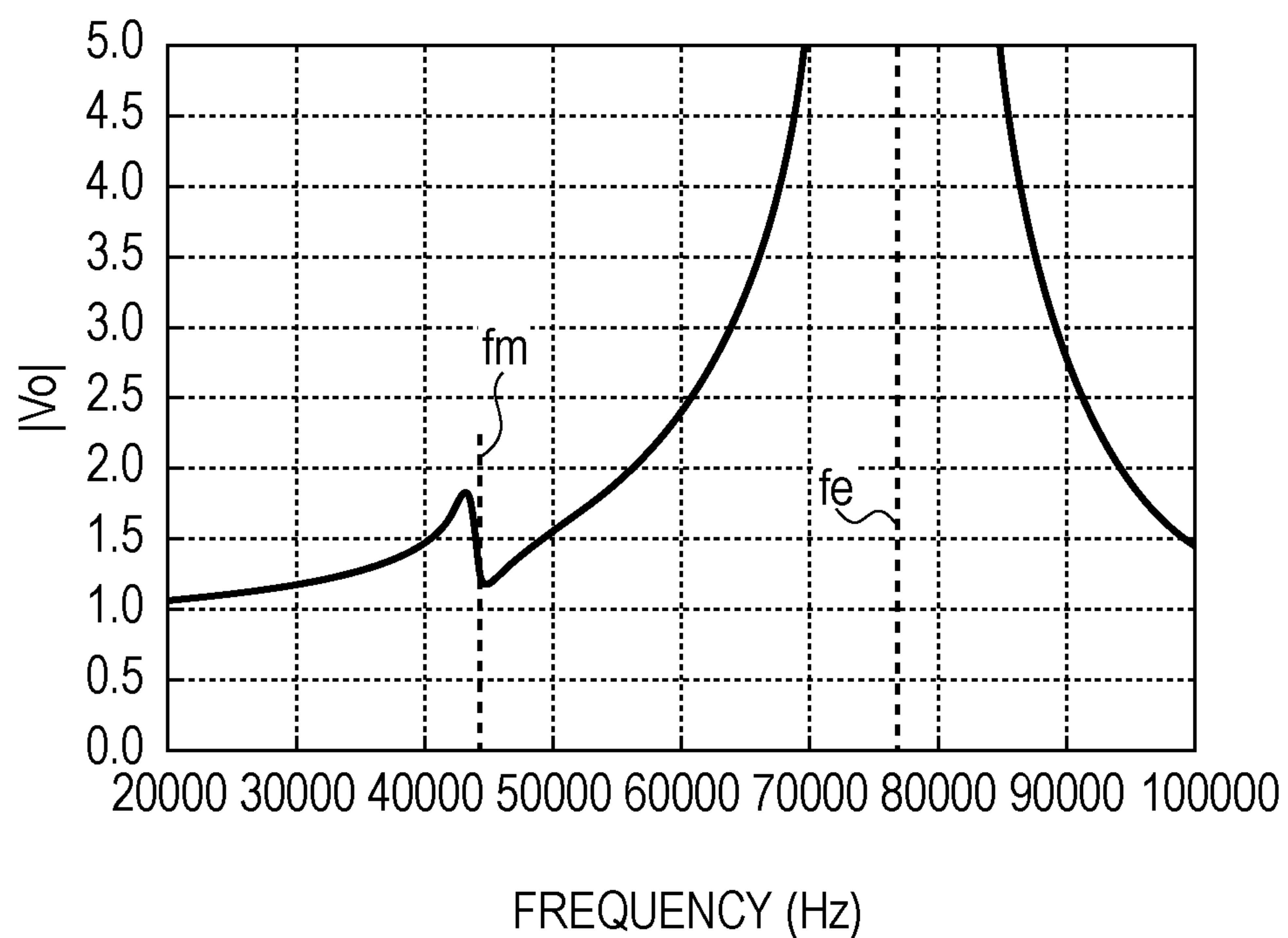


FIG. 3A

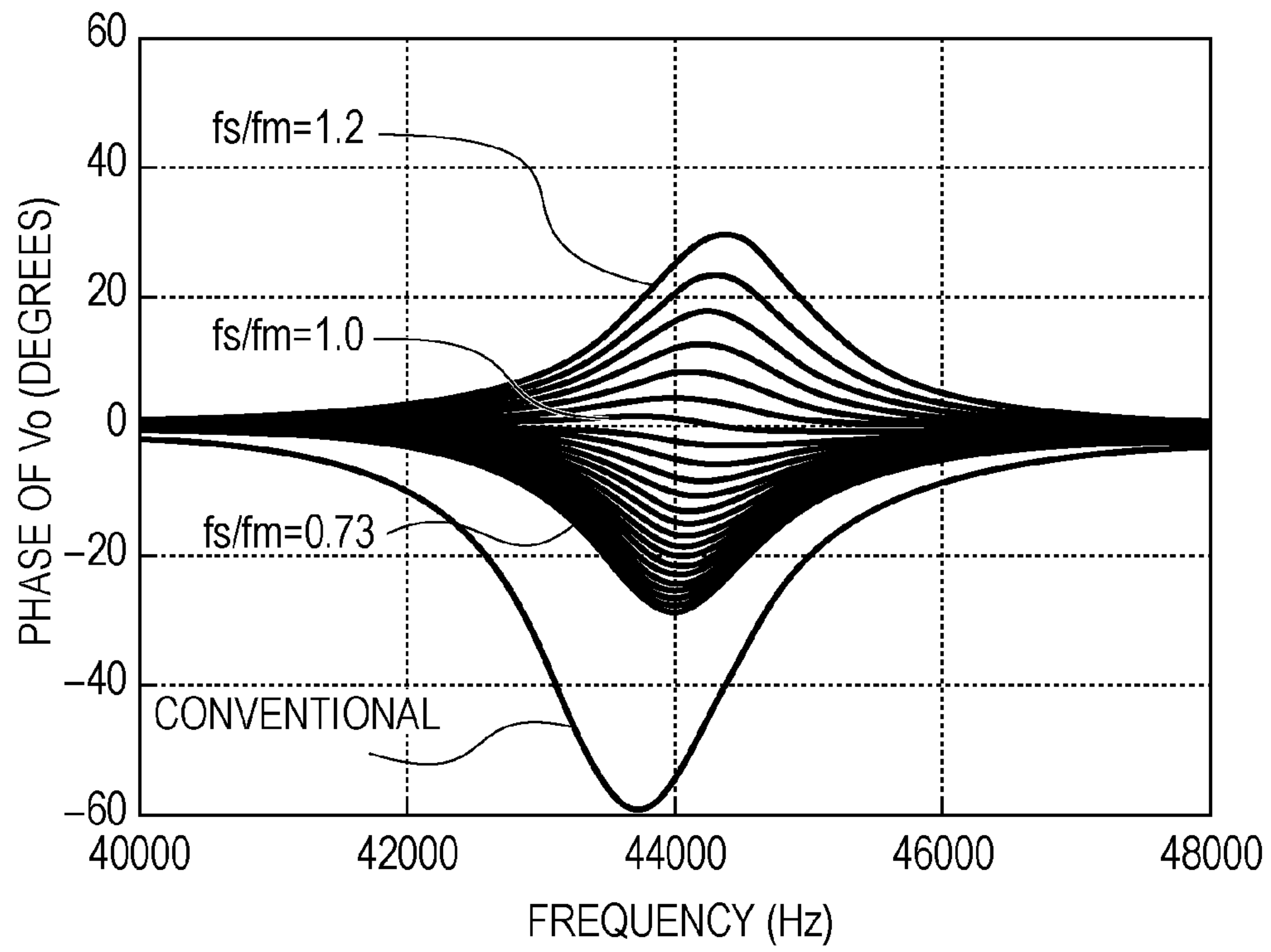


FIG. 3B

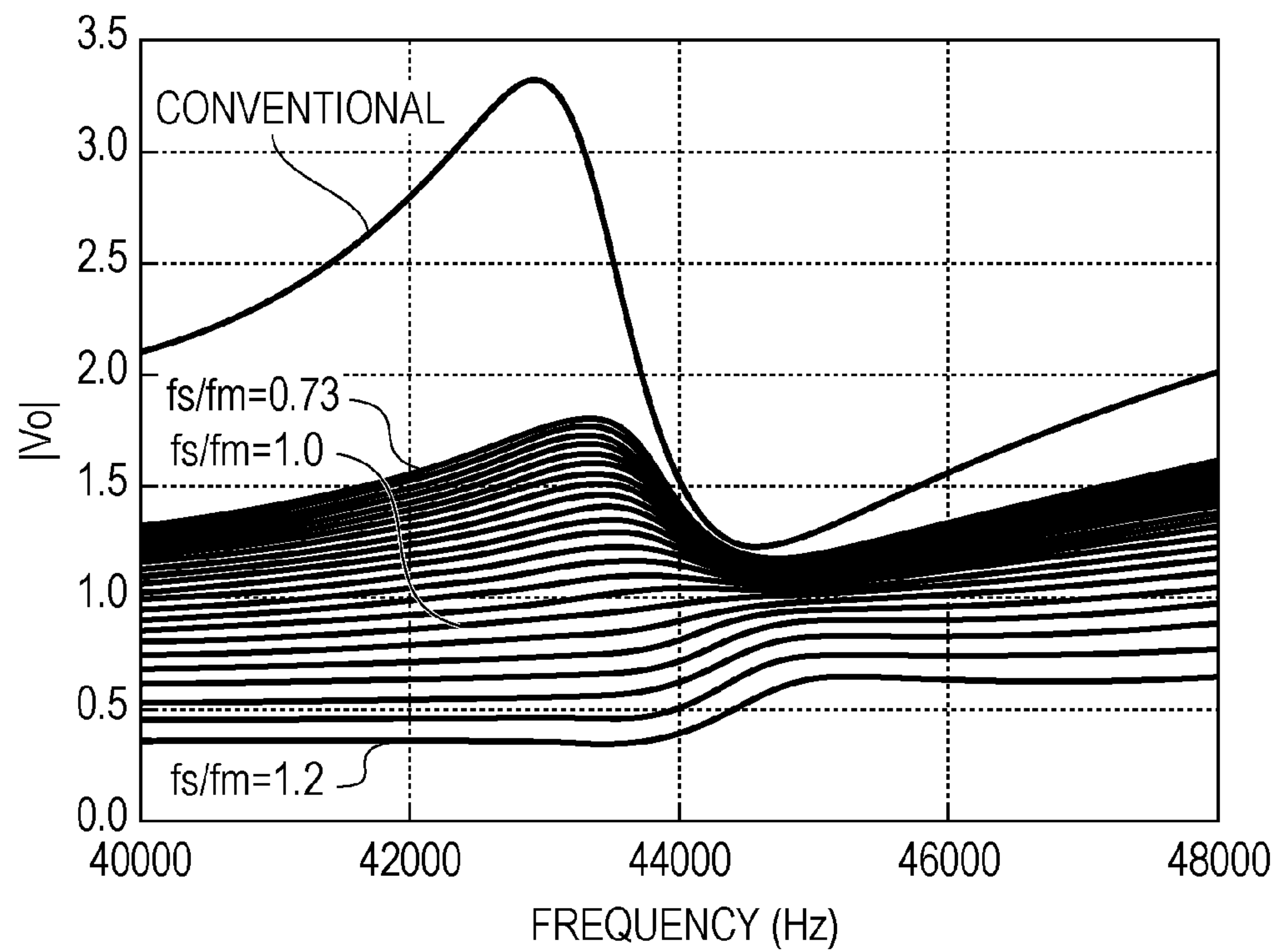




FIG. 4

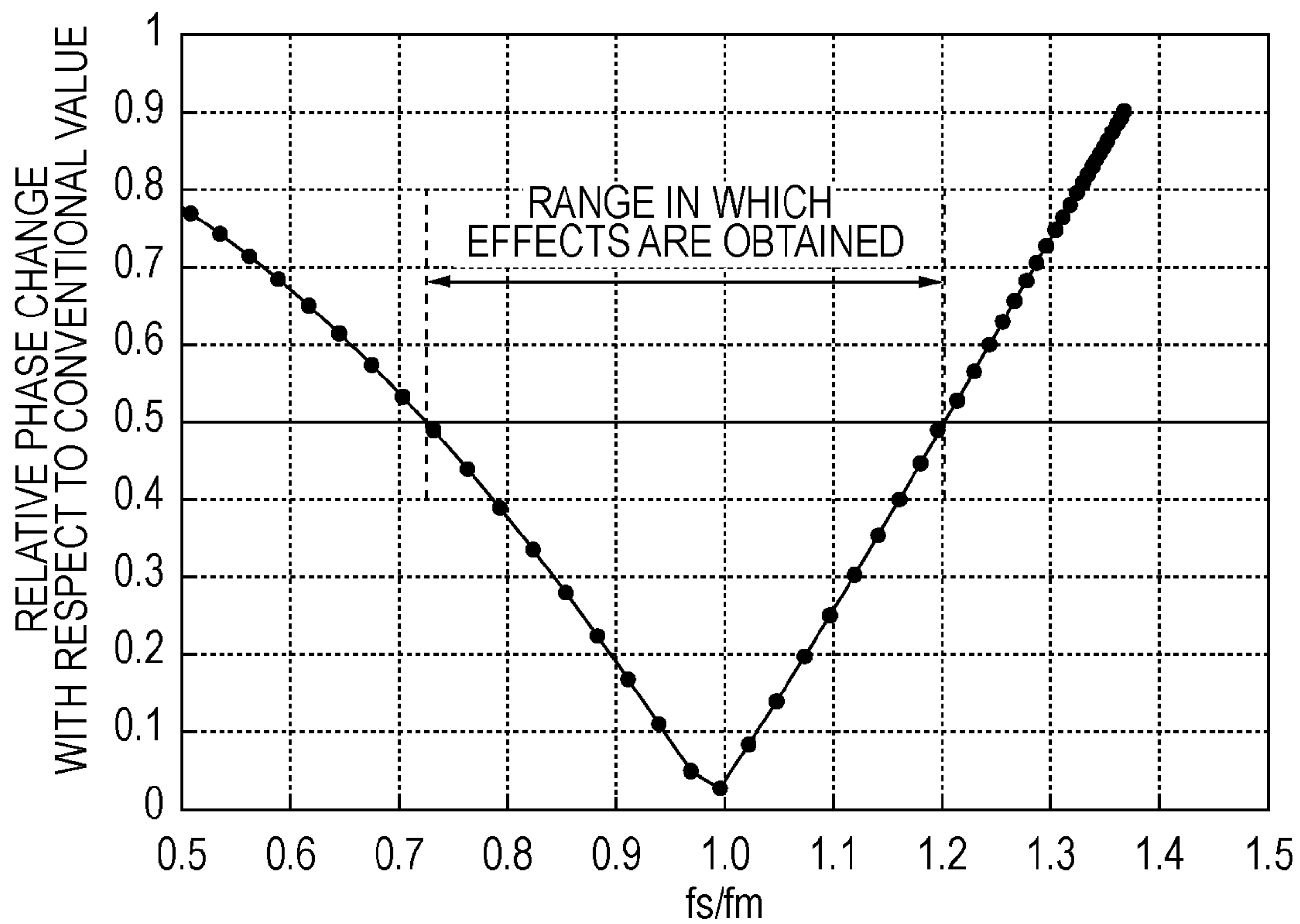


FIG. 5

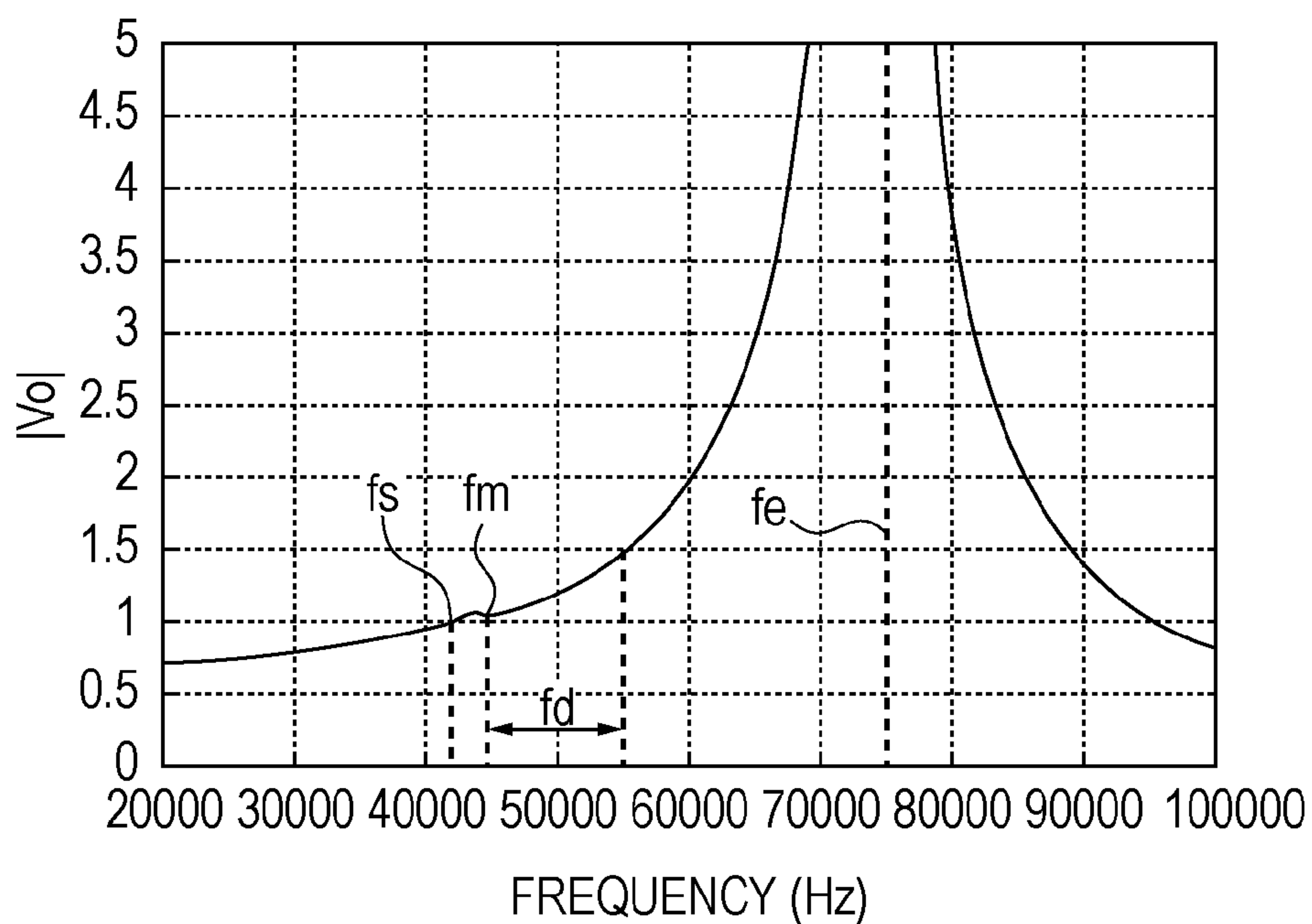


FIG. 6

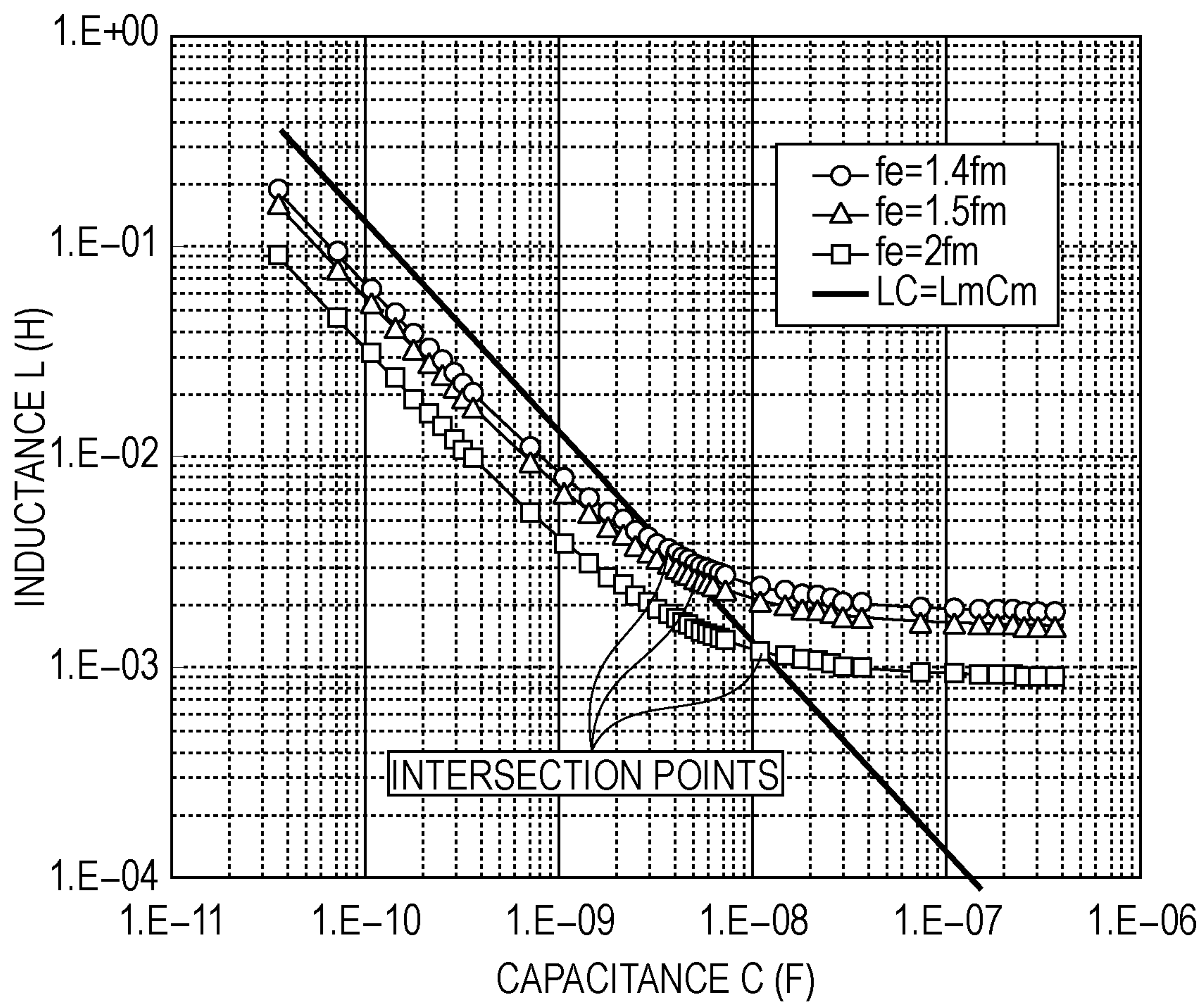


FIG. 7

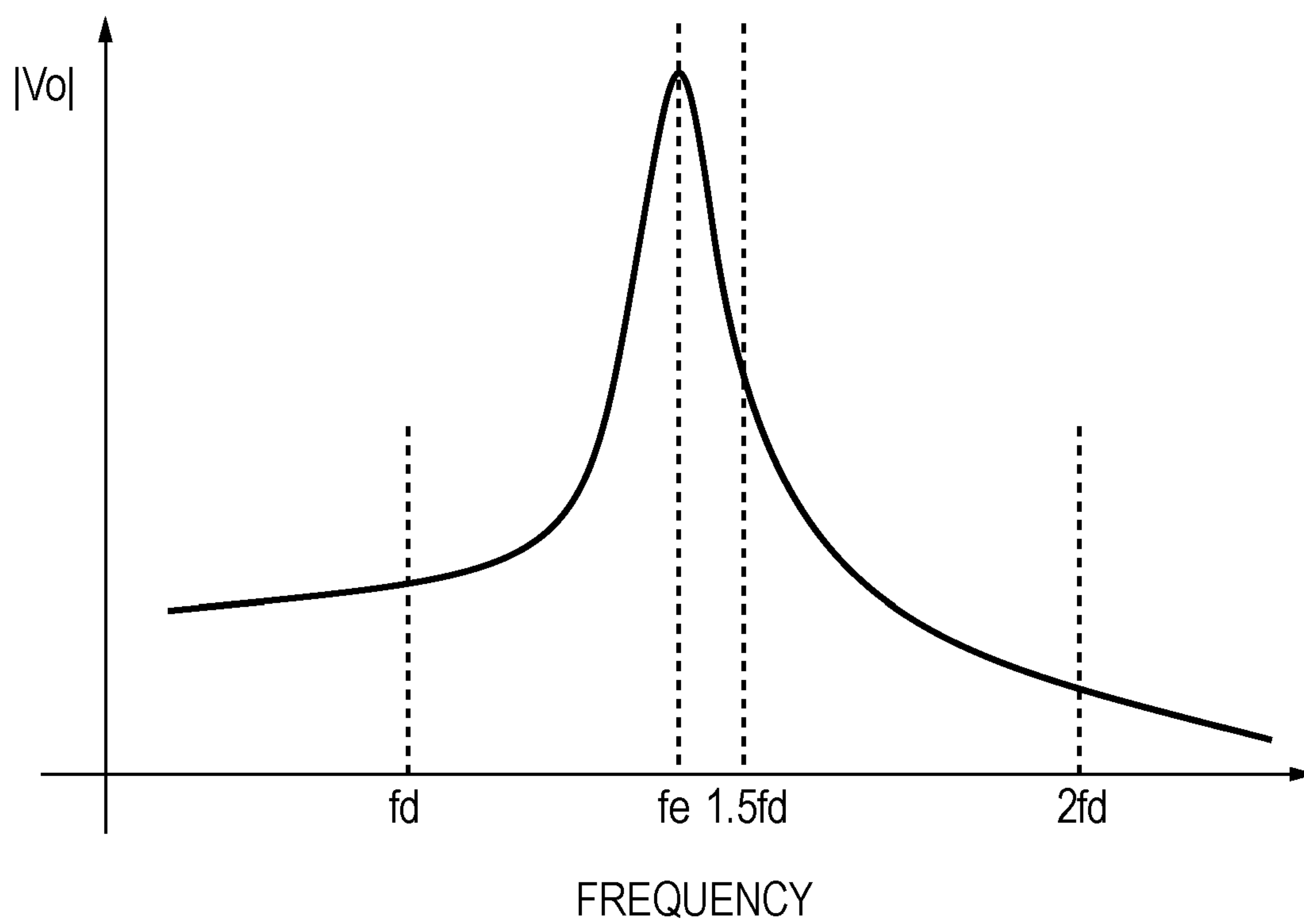


FIG. 8

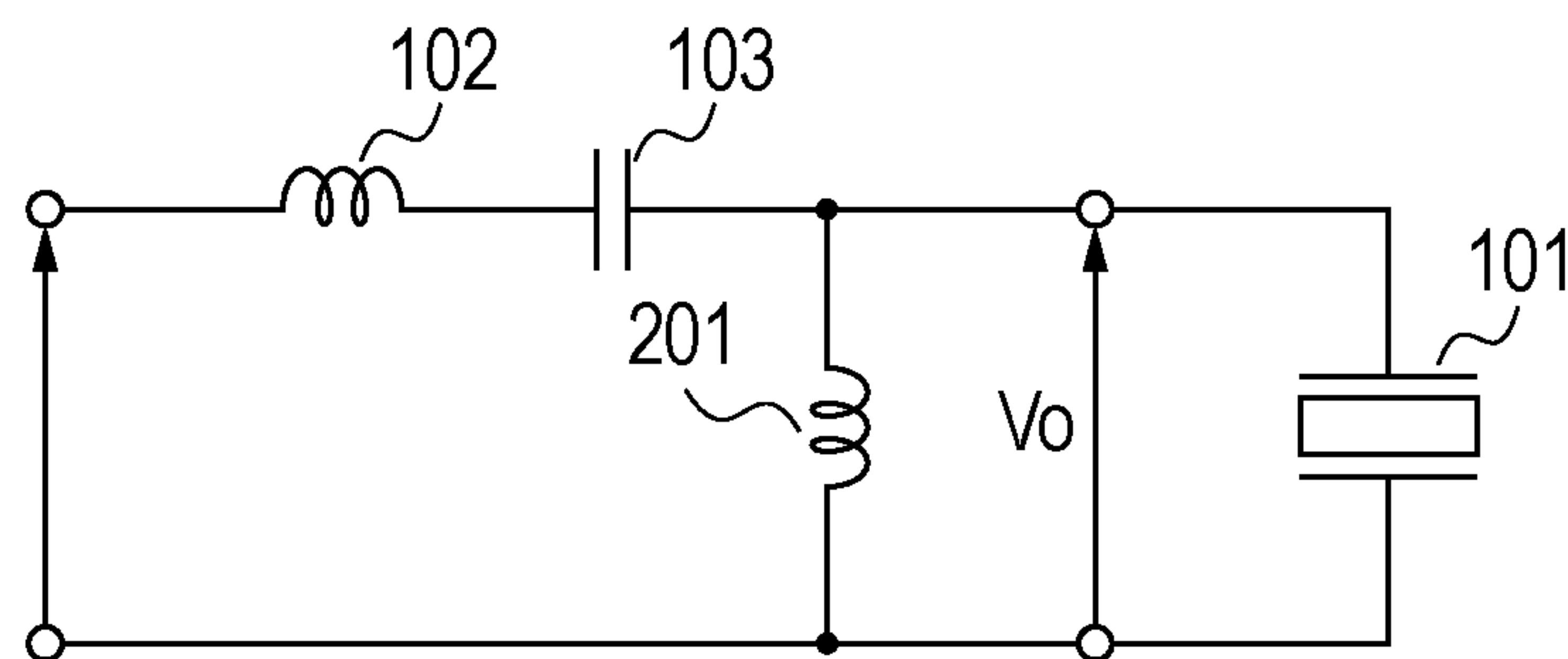




FIG. 9A

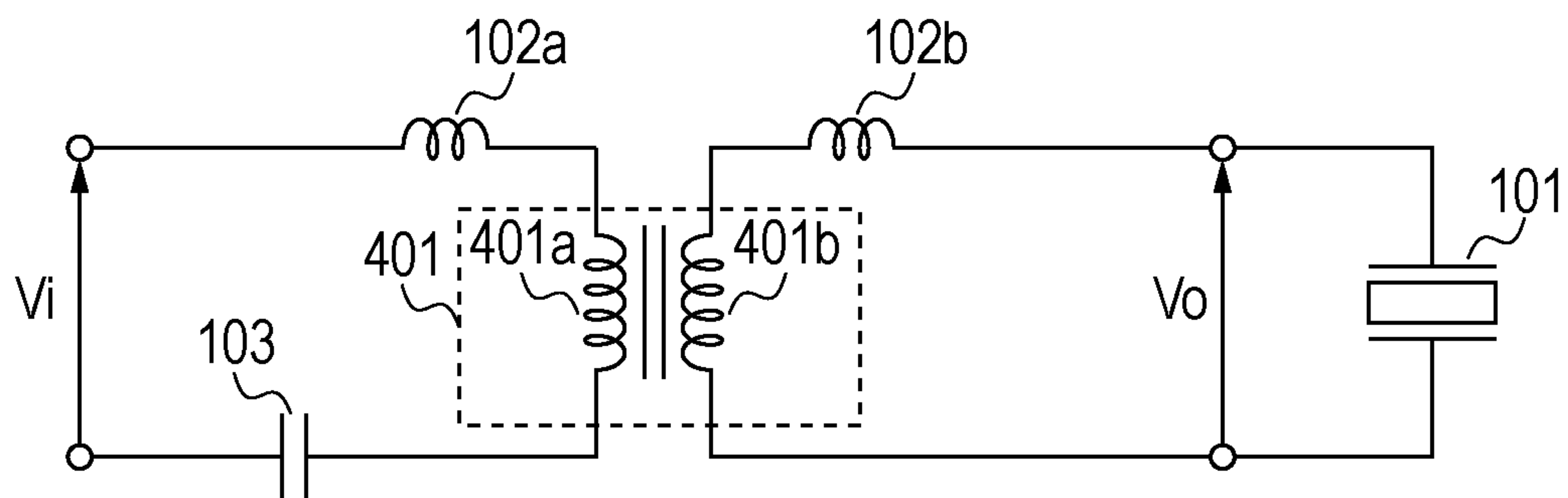


FIG. 9B

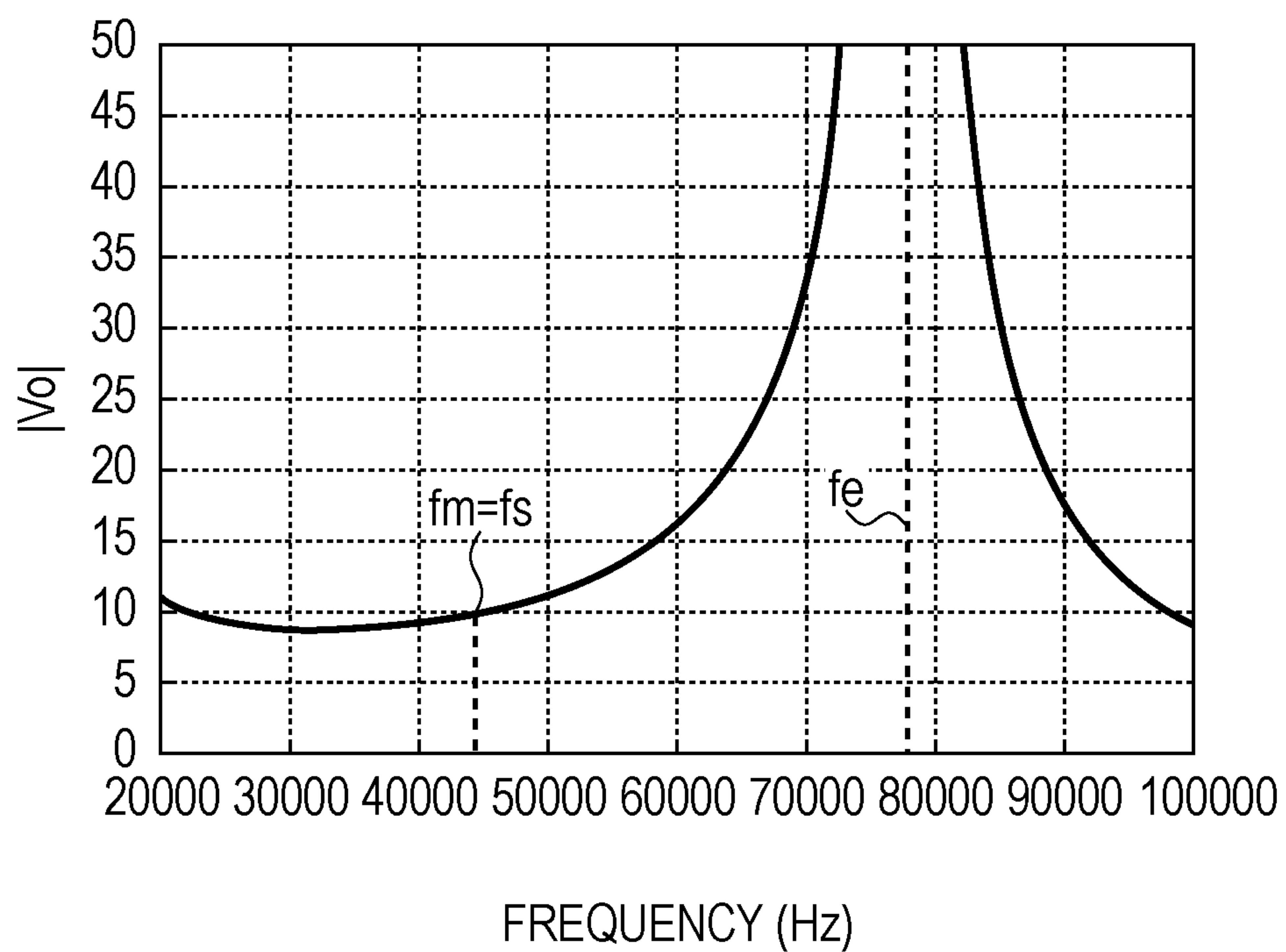


FIG. 10A

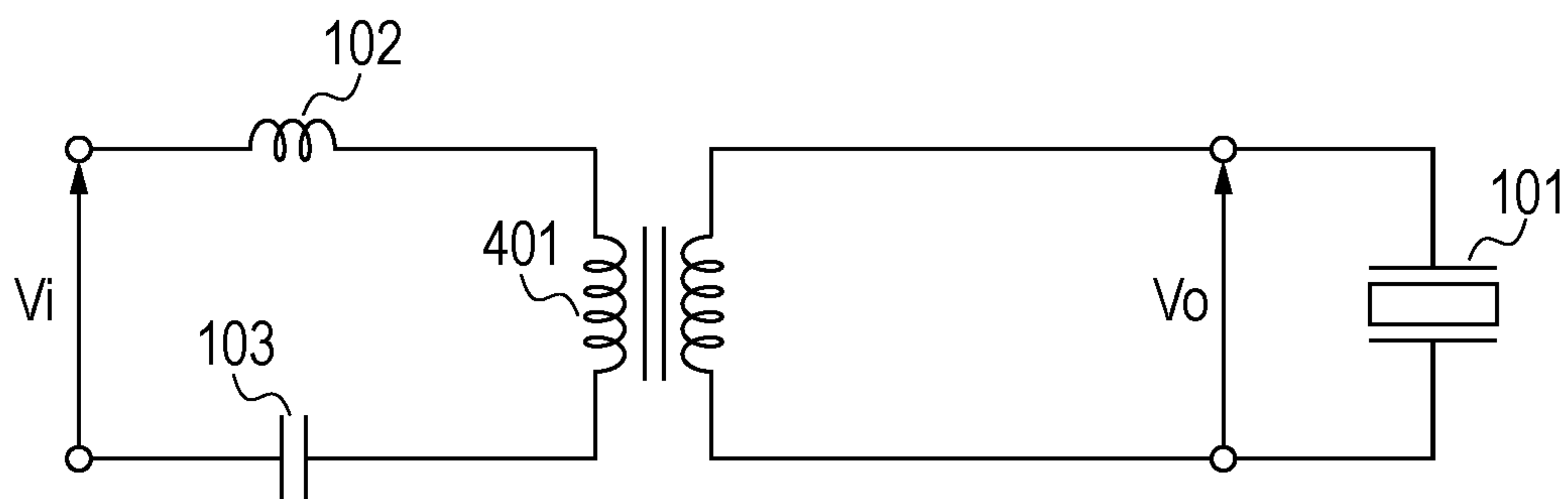


FIG. 10B

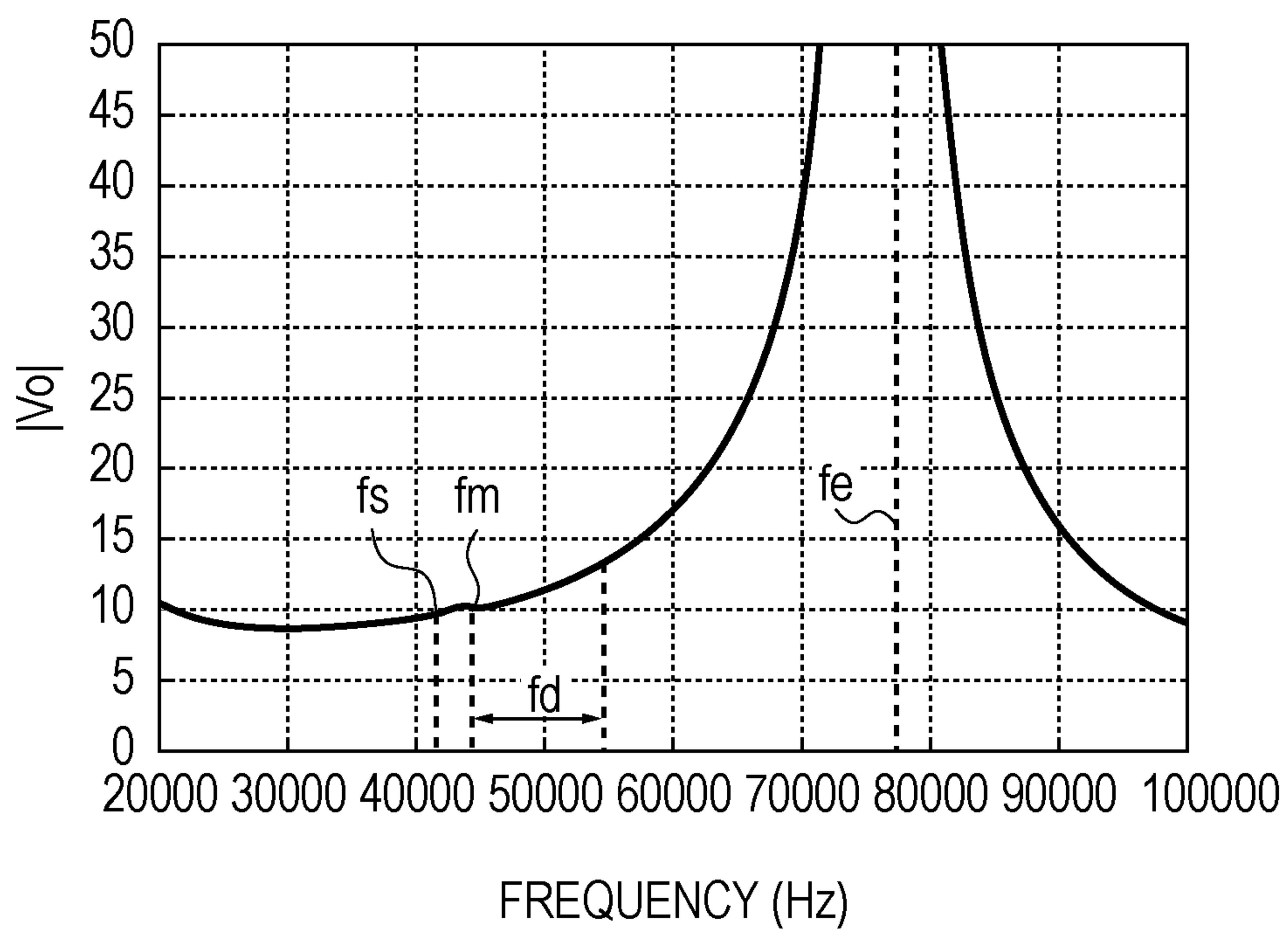


FIG. 11A

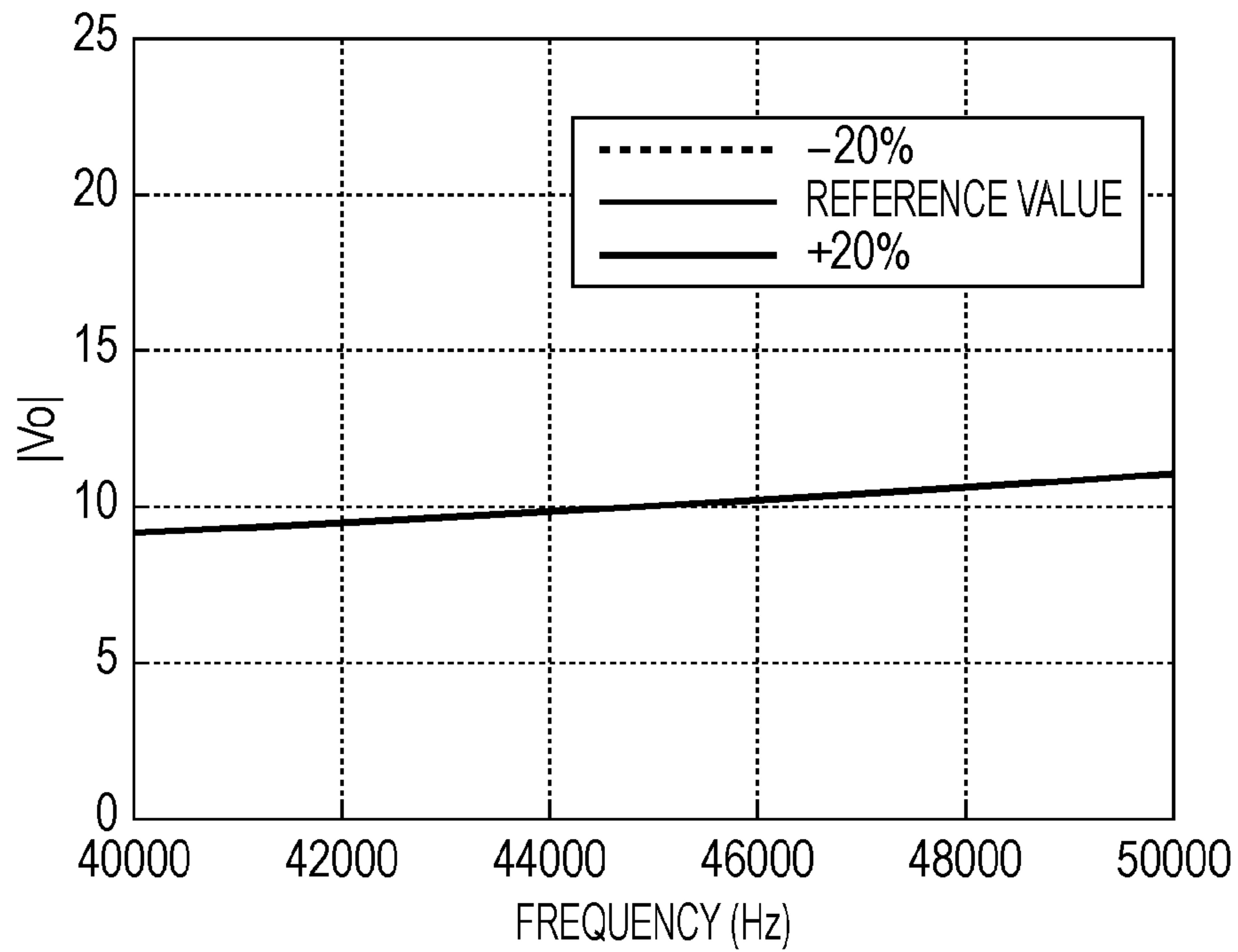


FIG. 11B

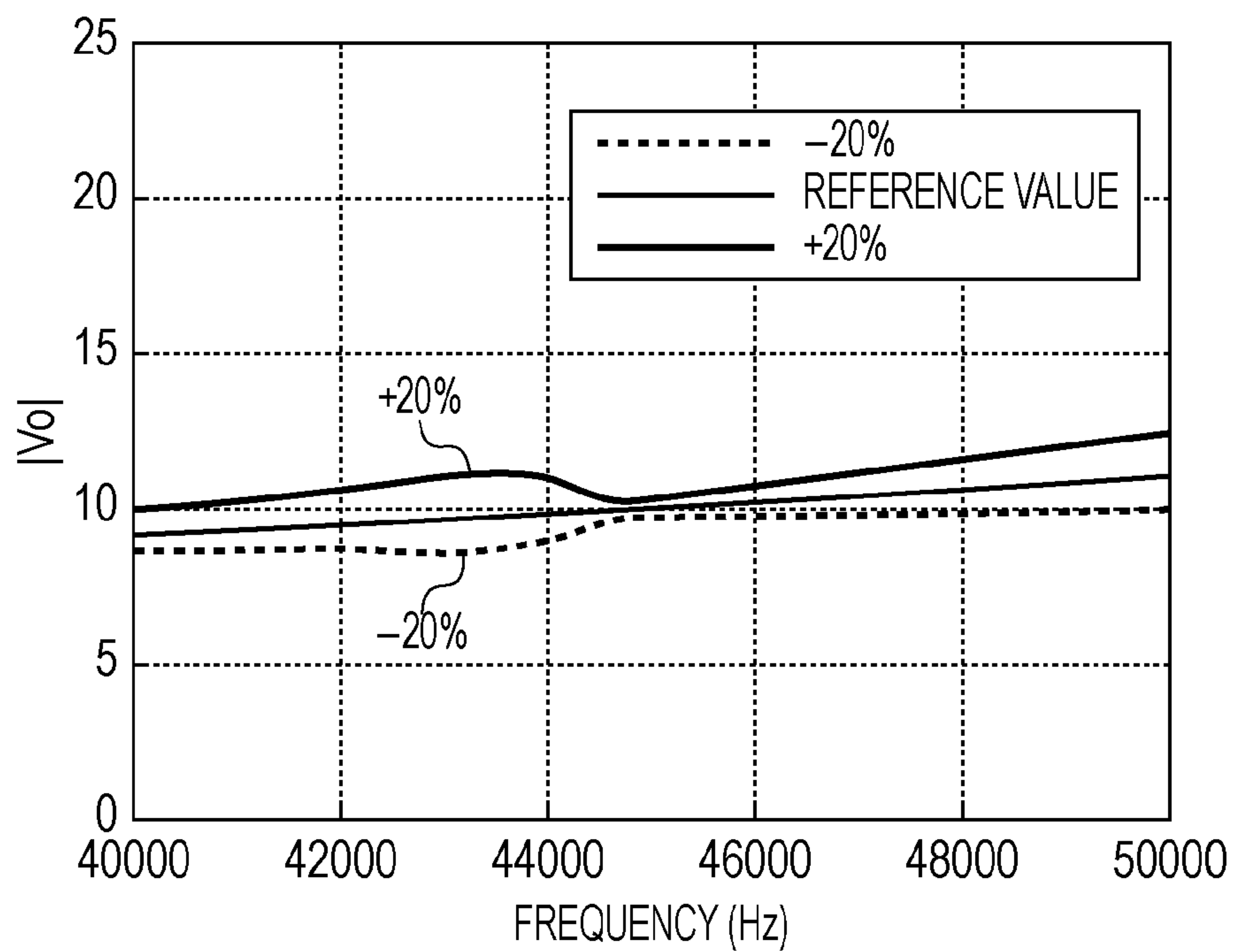


FIG. 12A

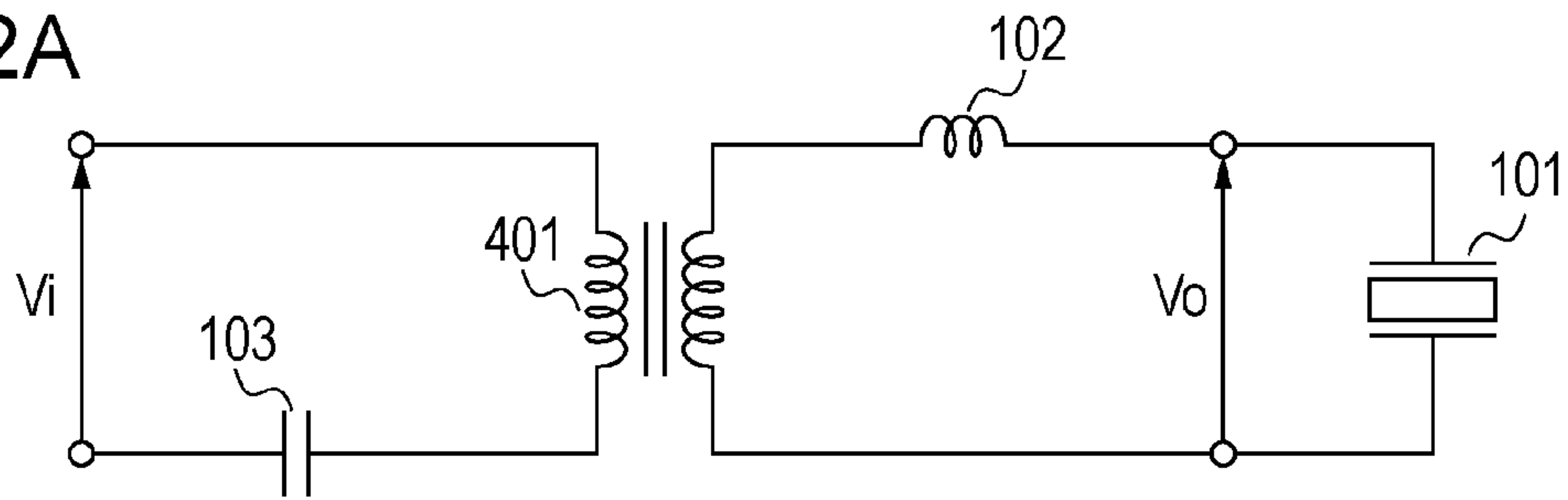


FIG. 12B

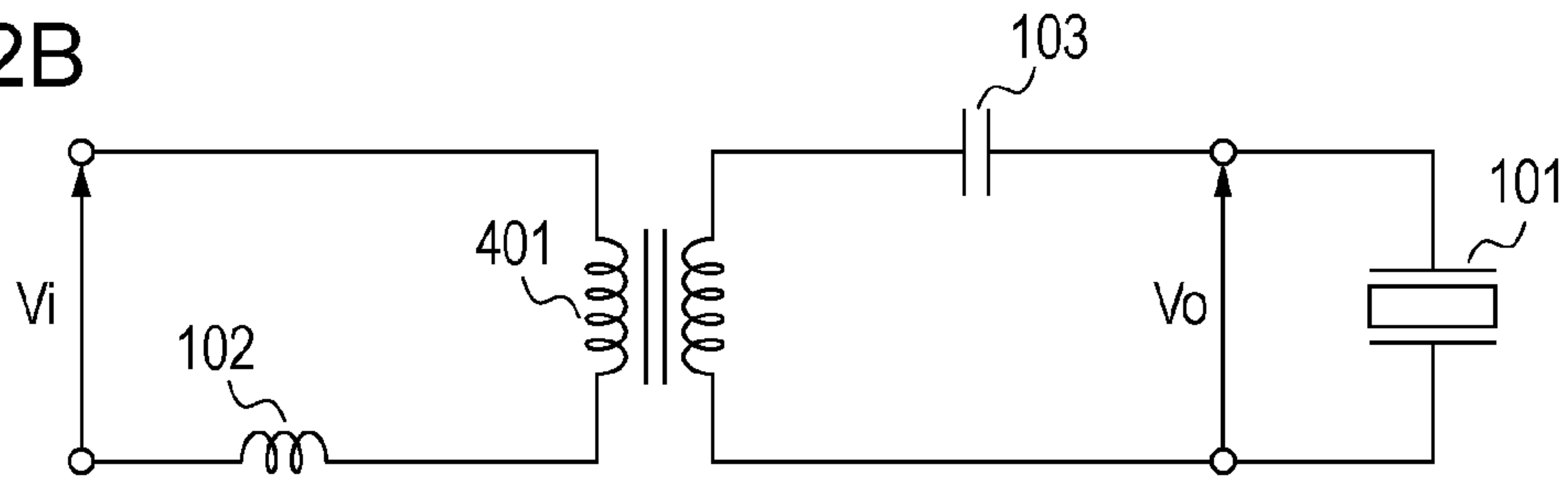


FIG. 12C

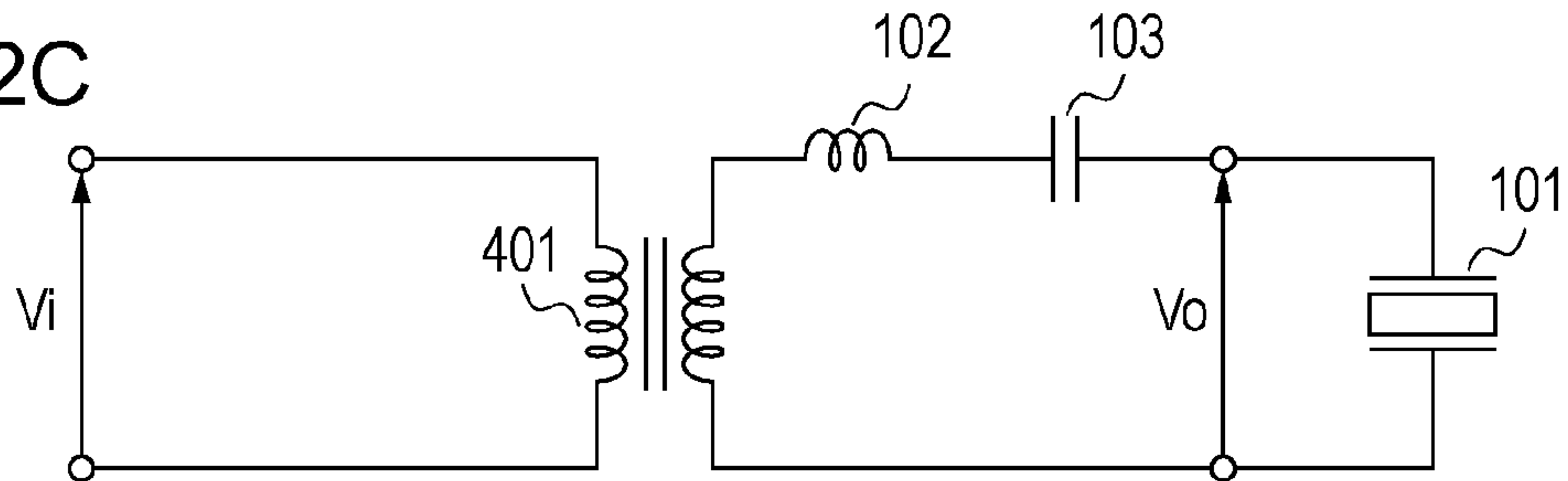


FIG. 12D

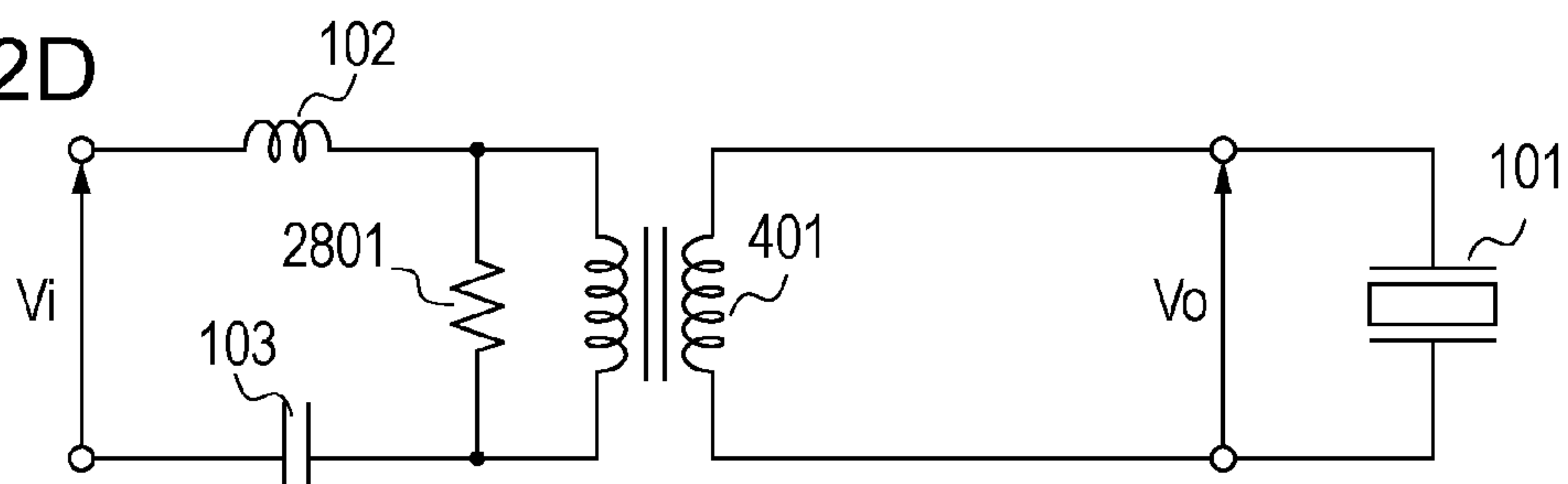


FIG. 12E

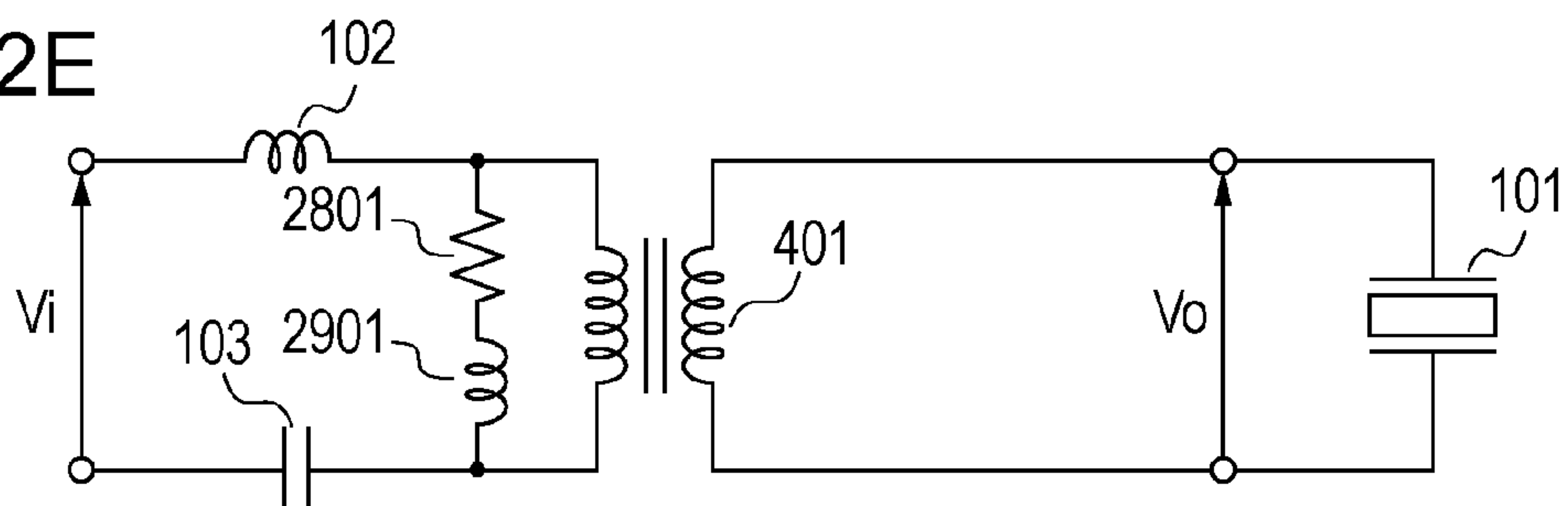


FIG. 13A

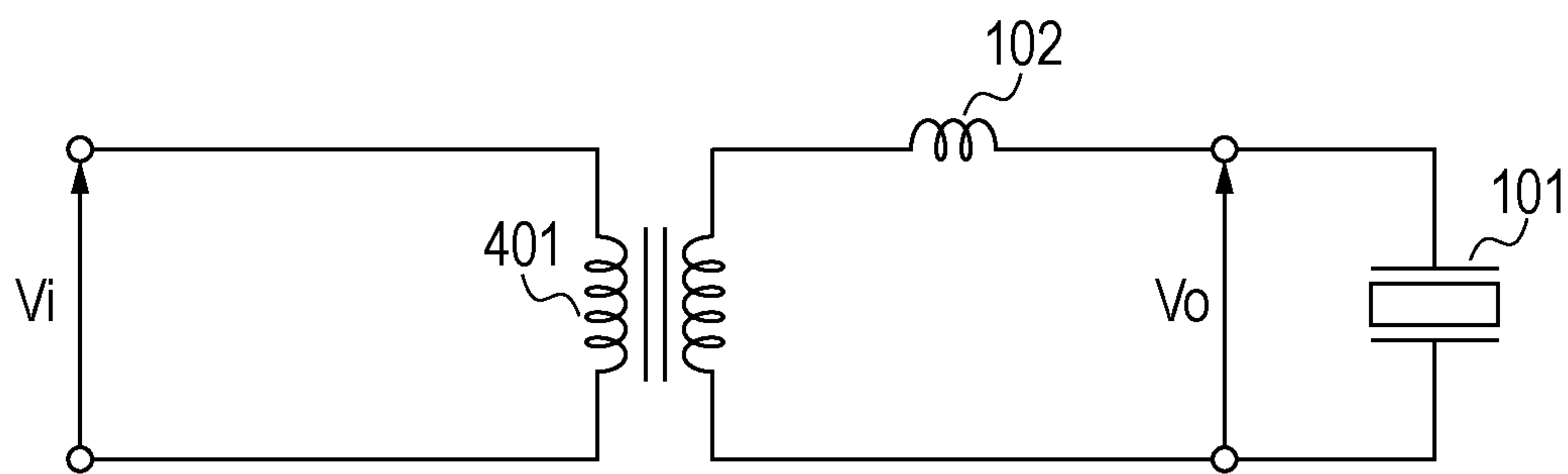


FIG. 13B

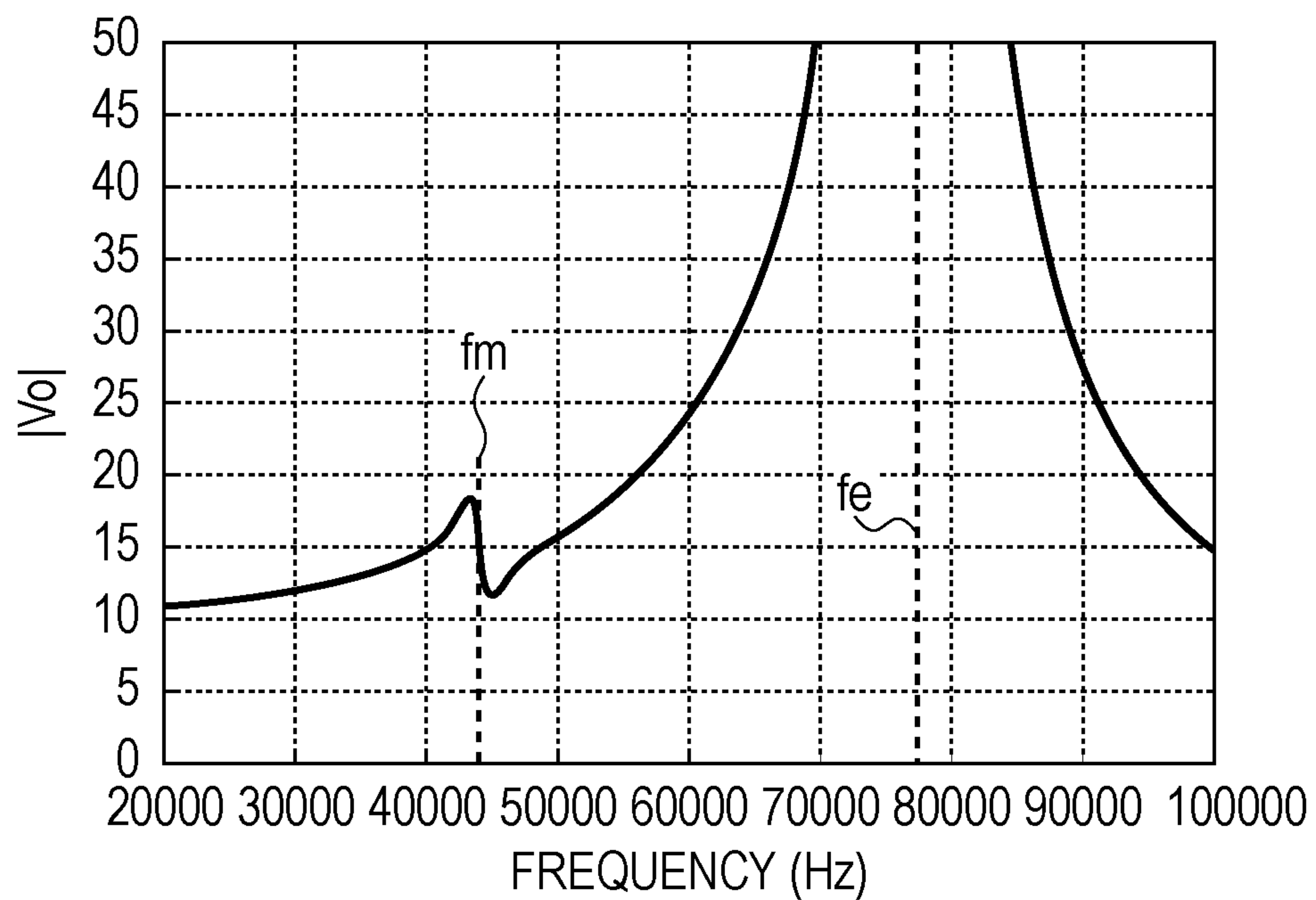


FIG. 14A

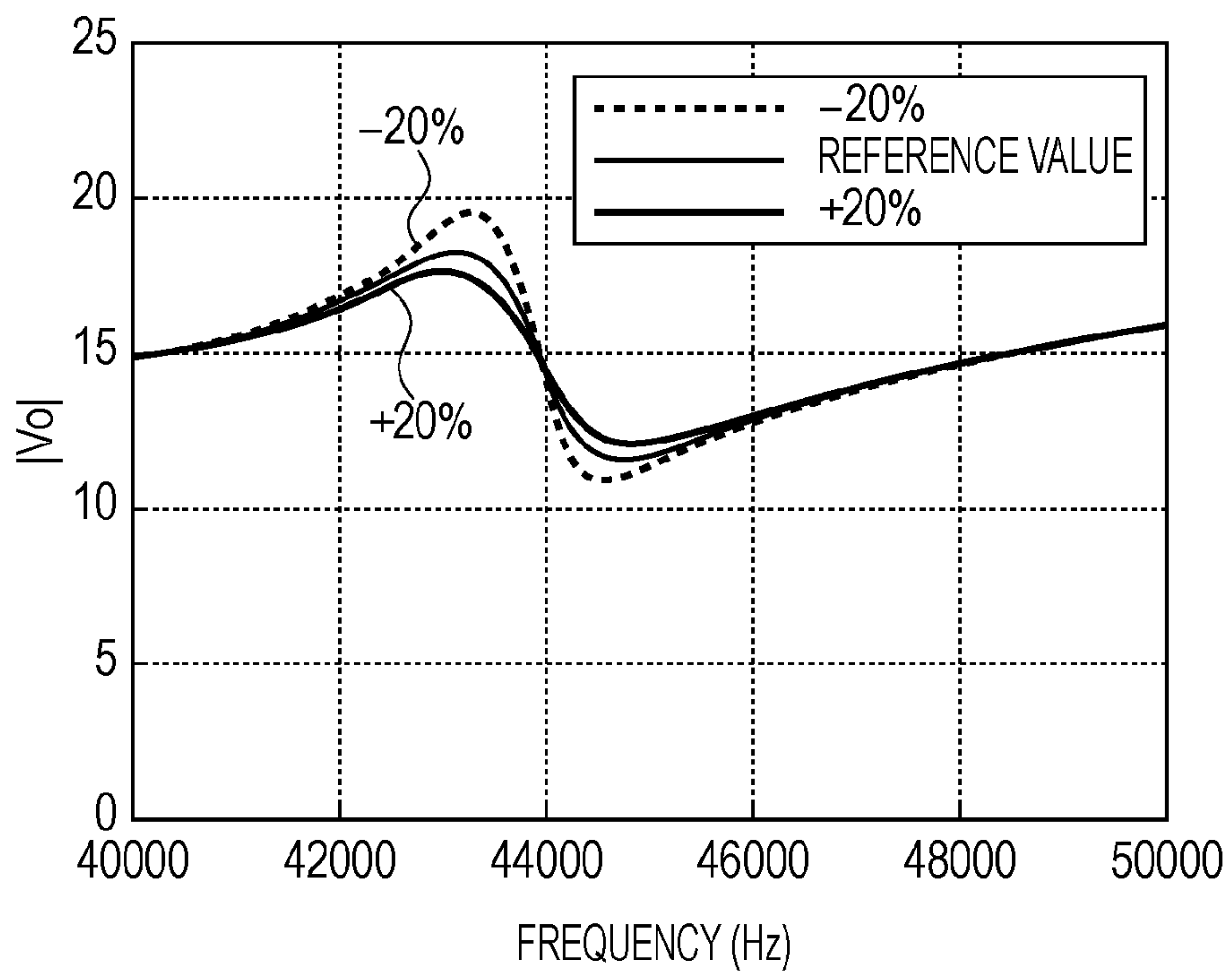


FIG. 14B

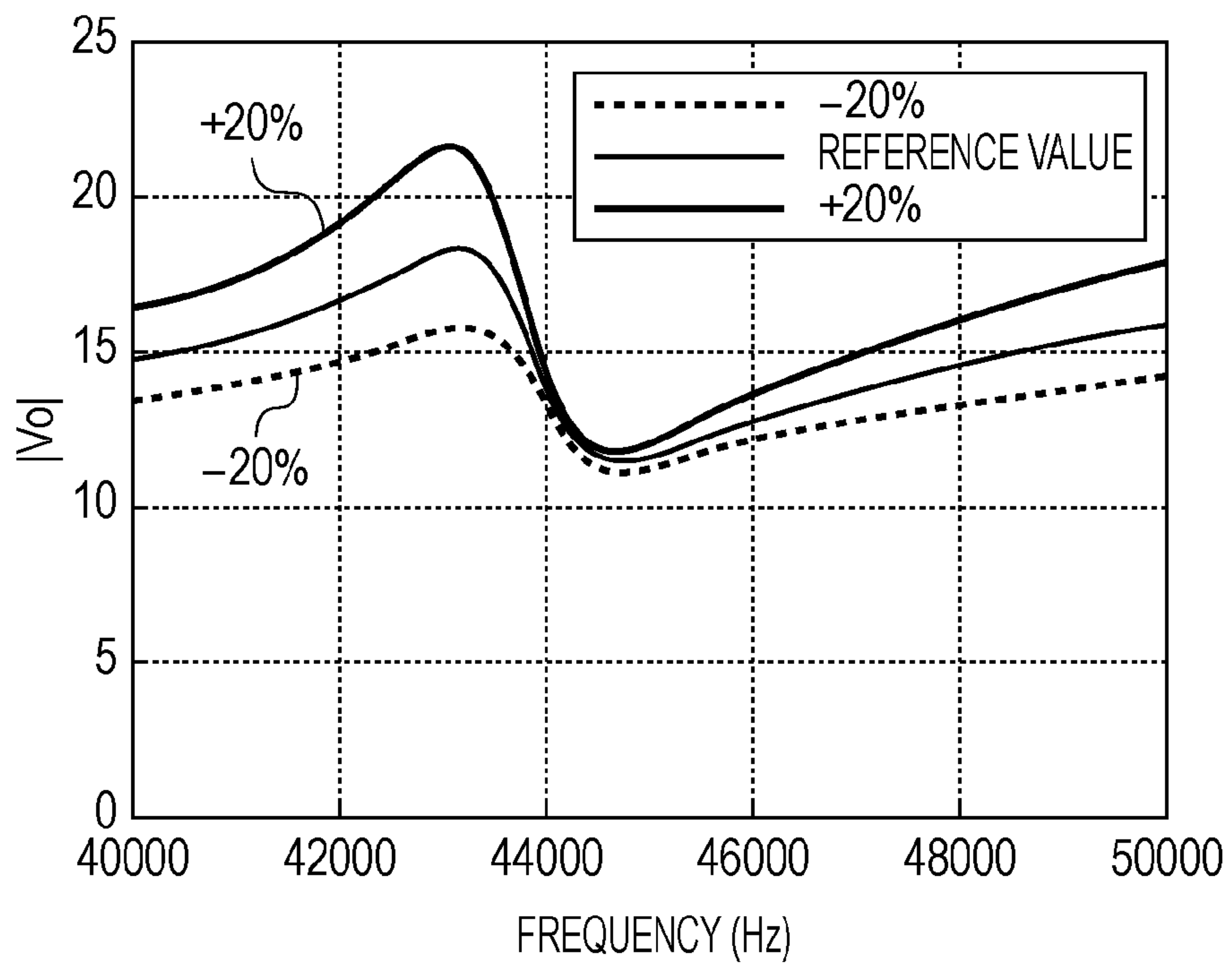




FIG. 15

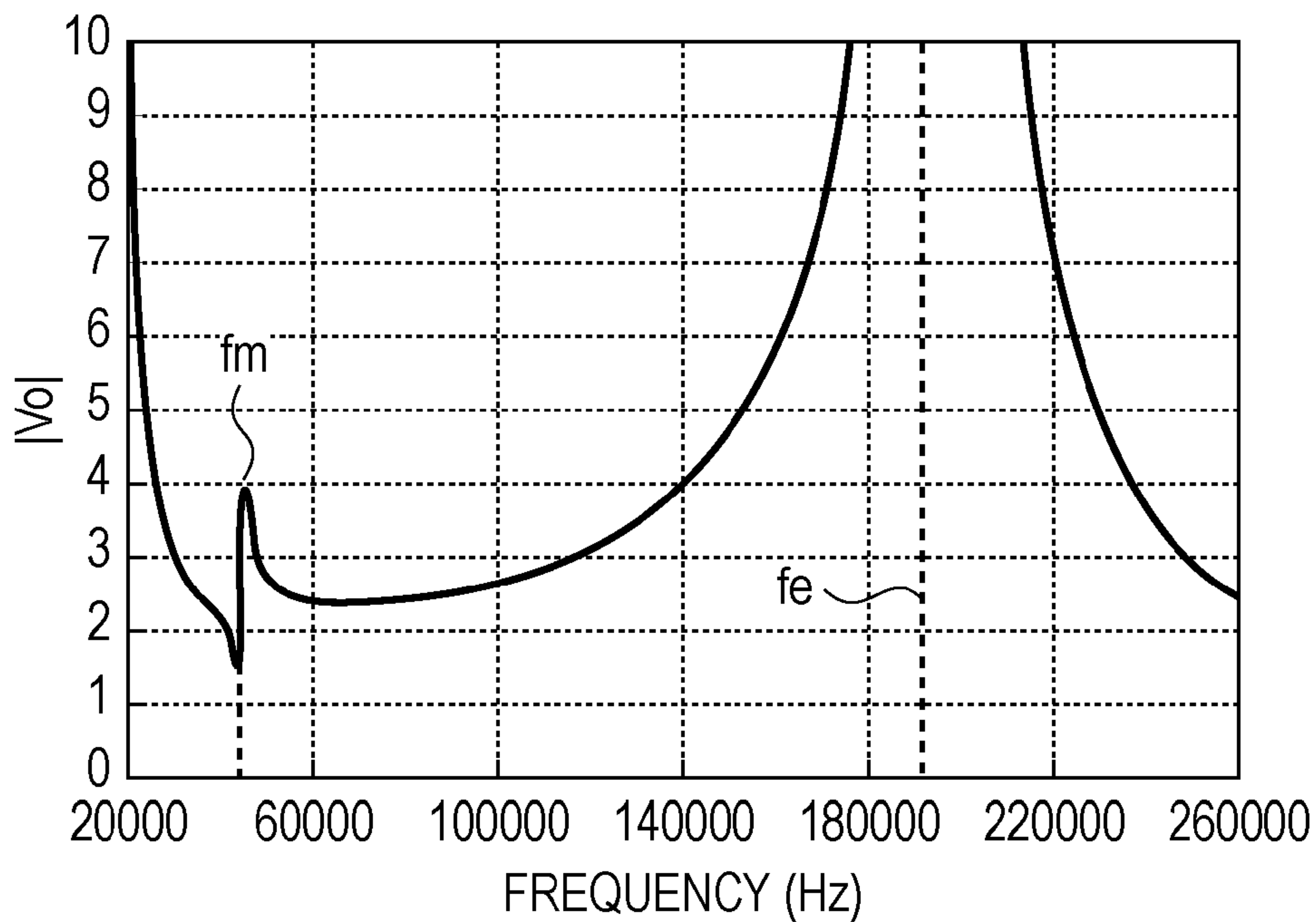
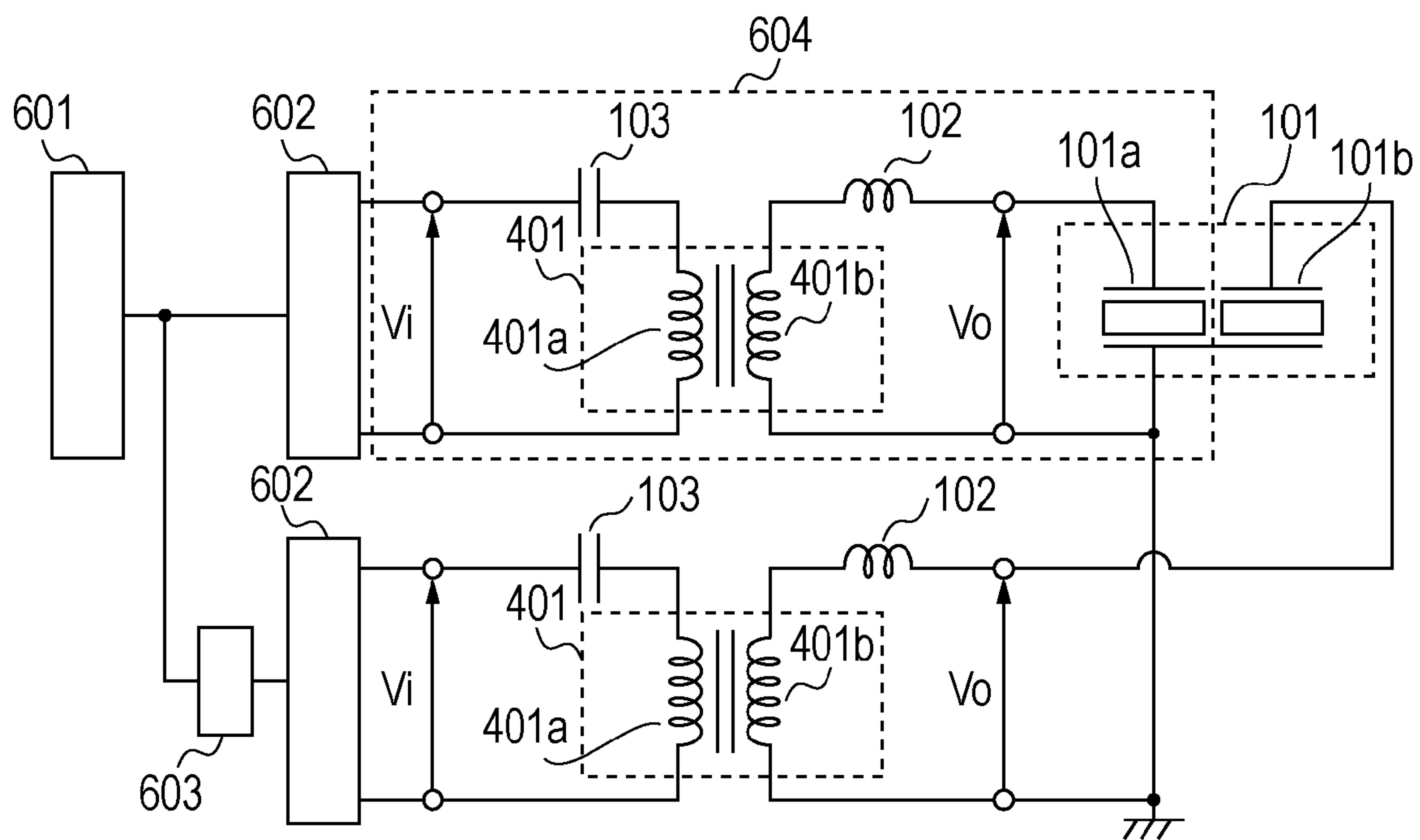


FIG. 16



## DRIVING CIRCUIT FOR VIBRATION-TYPE ACTUATOR

### CROSS REFERENCE TO RELATED APPLICATIONS

The present application is a continuation of U.S. patent application Ser. No. 14/017,089, filed on Sep. 3, 2013, which is a continuation of and claims priority from U.S. patent application Ser. No. 12/905,993, filed on Oct. 15, 2010, which claims priority from Japanese Patent Application No. 2009-265234, filed Nov. 20, 2009, all of which are hereby incorporated by reference herein in their entirety.

### BACKGROUND OF THE INVENTION

#### 1. Field of the Invention

The present invention relates to a driving circuit configured to drive a vibration-type actuator.

#### 2. Description of the Related Art

The vibration-type actuator is a non-electromagnetically driving actuator configured to generate a high-frequency vibration in an electro-mechanical energy conversion element such as a piezoelectric element by applying an alternating voltage to the electro-mechanical energy conversion element whereby vibration energy is output in the form of continuous mechanical motion. The vibration-type actuators are classified into a standing wave type and a traveling wave type according to types of generated vibrations.

FIG. 16 illustrates a conventional driving circuit configured to drive a vibration-type actuator of the traveling wave type (see Japanese Patent Publication No. 5016277). A vibration member **101** is a combination of a piezoelectric element and an elastic element. The piezoelectric element is applied with an alternating voltage via driving electrodes **101a** and **101b**. An oscillator **601** generates an alternating signal corresponding to a driving frequency. A switching circuit **602** operates such that a switching element in the switching circuit **602** turns on and off in accordance with the alternating signal supplied from the oscillator **601** thereby generating an alternating voltage. The switching circuit **602** is connected to a DC voltage source (not shown) such that the alternating voltage is generated from a DC voltage supplied from the DC voltage source.

The actuator shown in FIG. 16 employs a two-phase driving scheme. In this scheme, alternating voltages with different phases are provided from two parts of the driving circuit. These two parts of the driving circuit are similar except that the phase of an input alternating voltage is shifted by  $\pm 90^\circ$  by a  $90^\circ$ -phase shifter **603**. Therefore, the following explanation is given only for a part **604** that is one of these two parts.

The alternating voltage  $V_i$  output from the switching circuit **602** is applied to a primary coil **401a** of a transformer **401**, and stepped up by an amount corresponding to the turn ratio of the secondary coil **401b** to the primary coil **401a** of the transformer **401**. The stepped-up alternating voltage  $V_o$  is passed through an inductor **102** connected in series to the secondary coil **401b** of the transformer **401** to remove harmonic components from the waveform of the alternating voltage  $V_o$ . The resultant alternating voltage  $V_o$  is applied to the driving electrode **101a**. In the actuator disclosed in Japanese Patent Publication No. 5016277, a capacitor **103** is connected to the primary coil **401a** of the transformer **401** such that series resonance occurs between the capacitor **103** and the primary coil **401a** whereby the frequency characteristic of the alternating voltage  $V_o$  has a peak. Note that the series resonance frequency of the series of the capacitor **103** and the

primary coil **401a** of the transformer **401** is set to be equal to the resonance frequency of the vibration member **101**. This configuration makes it possible to adjust the alternating voltage  $V_o$  by controlling the driving frequency even when a change occurs in the resonance frequency of the vibration member **101**, whereby it is possible to reduce the power consumption.

### SUMMARY OF THE INVENTION

In the conventional driving circuit for the traveling-wave vibration actuator, a great change occurs in the alternating voltage  $V_o$  applied to the vibration member **101** in a frequency range from a starting frequency to an operation frequency corresponding to a specified number of rotations, i.e., the frequency characteristic of the alternating voltage  $V_o$  has a steep gradient close to the resonance frequency of the vibration member **101**. This results in a change in voltage amplitude, which causes degradation in responsiveness to a driving speed, which in turn causes degradation in controllability. In view of the above, the present invention provides a driving circuit having a small change in output voltage over a full driving frequency range from a starting frequency to an operation frequency.

In an aspect of the present invention, a driving circuit configured to drive a vibration member comprising an electro-mechanical energy conversion element includes a transformer connected in parallel to the electro-mechanical energy conversion element and comprising a primary coil configured such that an alternating voltage is applied to the primary coil, and a secondary coil connected to the electro-mechanical energy conversion element in parallel, and an inductor connected to the primary coil in series, wherein parameters of the driving circuit are set such that, when a frequency of a peak voltage applied to the electro-mechanical energy conversion element is denoted by  $f_e$  and a driving frequency of the vibration member is denoted by  $f_d$ , a condition  $f_e < 1.5 \cdot f_d$  is satisfied.

In an aspect of the present invention, there is provided a driving circuit to drive a vibration-type actuator including a vibration member and a moving member. The vibration member includes an electro-mechanical energy conversion element and may generate a vibration wave in response to an alternating voltage applied to the electro-mechanical energy conversion element. The moving member is in contact with the vibration member and may move in response to the vibration wave relative to the vibration member. In this aspect, the driving circuit includes a transformer an inductor, and a capacitor. The transformer includes a primary coil and a secondary coil connected in parallel to the electro-mechanical energy conversion element. An alternating voltage may be applied to the primary coil. The inductor and the capacitor may be located at least one of a primary side and a secondary side of the transformer such that the inductor and the capacitor are connected in series to the electro-mechanical energy conversion element. Here, parameters of the driving circuit may be set such that when a series resonance frequency of the inductor and the capacitor is denoted by  $f_s$  and a resonance frequency of the vibration member is denoted by  $f_m$ , a condition  $0.73 \cdot f_m < f_s < 1.2 \cdot f_m$  is satisfied.

Thus, the driving circuit according to any aspect of the present invention provides an output voltage with a small change over the full frequency range from the starting frequency to the operation frequency and thus provides improved frequency controllability.



Further features of the present invention will become apparent from the following description of exemplary embodiments with reference to the attached drawings.

#### BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. 1A and 1B are diagrams illustrating a driving circuit configured to drive a vibration-type actuator according to an embodiment of the present invention, and FIG. 1C is a diagram illustrating a simulated characteristic thereof.

FIG. 2A is a diagram illustrating a comparative example of a driving circuit configured to drive a vibration-type actuator according to a conventional technique, and FIG. 2B is a diagram illustrating a simulated characteristic thereof.

FIG. 3A is a diagram illustrating a simulation result in terms of a phase of an alternating voltage  $V_0$ , and FIG. 3B is a diagram illustrating a simulation result in terms of a change in alternating voltage  $V_0$  as a function of a frequency.

FIG. 4 is a diagram illustrating a simulation result in terms of a relative change in phase with respect to a change that occurs in a conventional technique as a function of  $f_s/f_m$ .

FIG. 5 is a diagram illustrating a simulation result in terms of a frequency characteristic of an alternating voltage  $V_0$  for a case where a series resonance frequency  $f_s$  is lower than a resonance frequency  $f_m$  of a vibration member.

FIG. 6 is a diagram illustrating a relationship between inductance of an inductor and capacitance of a capacitor for a plurality of peak frequencies  $f_e$  according to an embodiment of the present invention.

FIG. 7 is a diagram illustrating a frequency characteristic of an alternating voltage  $V_0$  for a case where  $f_e < 1.5 \cdot f_d$ .

FIG. 8 is a diagram illustrating a driving circuit configured to drive a vibration-type actuator according to a modified embodiment of the present invention.

FIG. 9A is a diagram illustrating a driving circuit configured to drive a vibration-type actuator according to an embodiment of the present invention, and FIG. 9B is a diagram illustrating a simulated characteristic thereof.

FIG. 10A is a diagram illustrating a driving circuit configured to drive a vibration-type actuator according to a modified embodiment of the present invention, and FIG. 10B is a diagram illustrating a simulated characteristic thereof.

FIGS. 11A and 11B are diagrams illustrating simulation results in terms of changes of an alternating voltage  $V_0$  due to a variation of a load and a variation of an inductor.

FIGS. 12A to 12E are diagrams illustrating driving circuits configured to drive a vibration-type actuator according to modified embodiments of the present invention.

FIG. 13A is a diagram illustrating a comparative example of a driving circuit using a transformer configured to drive a vibration-type actuator according to a conventional technique, and FIG. 13B is a diagram illustrating a simulated characteristic thereof.

FIGS. 14A and 14B are diagrams illustrating simulation results in terms of changes of an alternating voltage  $V_0$  due to a variation of a load and a variation of an inductor of a comparative example of a driving circuit.

FIG. 15 is a diagram showing a simulation result in terms of a frequency characteristic of an alternating voltage  $V_0$  that is output according to a condition described in Japanese Patent Publication No. 5016277.

FIG. 16 is a diagram illustrating a driving circuit disclosed in Japanese Patent Publication No. 5016277.

#### DESCRIPTION OF THE EMBODIMENTS

The driving circuit of the vibration-type actuator according to the present invention is described in further detail below

with reference to embodiments in conjunction with the accompanying drawings. The driving circuit according to the present invention is applicable to a vibration-type actuator that is configured as follows. That is, the vibration-type actuator driven by the driving circuit according to the present invention includes a vibration member having an electro-mechanical energy conversion element such as a piezoelectric element and an elastic element connected to the electro-mechanical energy conversion element, and also includes a moving member that is urged into contact with the elastic element and that moves relative to the vibration member. The electro-mechanical energy conversion element is applied with a plurality of alternating voltages that are different in phase such that a vibration wave is generated in the elastic element. The generated vibration wave causes the elastic element to have an elliptic motion at a driving part (in contact with the moving member) in the elastic element, and this elliptic motion causes the moving member to move relative to the vibration member.

In embodiments described below, it is assumed by way of example that the driving circuit includes two parts, i.e., a first-phase part and a second-phase part such that the piezoelectric element serving as the electro-mechanical energy conversion element is driven by alternative voltages with different phases output from the respective parts. In this configuration, the first-phase part and the second-phase part of the driving circuit are similar except that a phase of an alternating voltage input to each part is shifted by  $\pm 90^\circ$  by a  $90^\circ$  phase shifter **603**, and thus the following explanation is given only for one part (corresponding to the part **604** shown in FIG. **16**). Note that the present invention is not limited to the two-phase driving scheme, but the present invention is also applicable to other types of driving circuits such as a driving circuit configured to drive a traveling-wave-type actuator by alternating voltages with four or more phases, a driving circuit configured to drive a standing-wave-type actuator, etc. An oscillator that generates an alternative signal and a switching circuit are not essential parts of the present invention, and there is no particular restriction on these parts. Therefore, the following description is given only for a part which, in the driving circuit shown in FIG. **16**, receives an alternating voltage  $V_i$  and outputs an alternating voltage  $V_0$  applied to the vibration member **101**.

#### First Embodiment

##### Example in which an Inductor and a Capacitor are Connected in Series to a Vibration Member

Referring to FIGS. 1A to 1C, a driving circuit according to a first embodiment is described below. FIG. 1A illustrates the driving circuit of the vibration-type actuator according to the first embodiment. The driving circuit is configured such that an inductor **102** and a capacitor **103** are connected in series to the vibration member **101** (i.e., in series to the electro-mechanical energy conversion element). An inductance element such as a coil may be used as the inductor **102**, and a capacitance element such as a film capacitor may be used as the capacitor **103**. In the present embodiment of the invention, the series resonance frequency of the inductor **102** and the capacitor **103** is set to be substantially equal to the resonance frequency of the vibration member **101**.

An equivalent circuit of the vibration member **101** is described below with reference to FIG. 1B. FIG. 1B illustrates an equivalent circuit of the one-phase part of the vibration member **101**. The equivalent circuit of the vibration member **101** includes an RLC series circuit corresponding to



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a mechanically vibrating part (an equivalent coil **301b** with self-inductance  $L_m$ , an equivalent capacitor **301c** with capacitance  $C_m$ , and an equivalent resistor **301d** with resistance  $R_m$ ) and a capacitor **301a** with an intrinsic capacitance  $C_d$  of the vibration member **101**. Note that the capacitor **301a** is connected in parallel with the RLC series circuit.

Hereinafter, the series resonance frequency of the inductor **102** and the capacitor **103** is denoted by  $f_s$ , and the resonance frequency of the vibration member **101** is denoted by  $f_m$ . Furthermore, if the self-inductance of the inductor **102** is denoted by  $L$ , and the capacitance of the capacitor **103** is denoted by  $C$ , then  $f_s$  and  $f_m$  are given as follows.

$$f_s = 1/(2\pi\sqrt{LC}) \quad (1-1)$$

$$f_m = 1/(2\pi\sqrt{L_m C_m}) \quad (1-2)$$

By setting  $f_s$  to be substantially equal to  $f_m$ , it becomes possible to obtain a gradual change in frequency characteristic of the alternating voltage  $V_o$  in a range close to  $f_m$ .

FIG. 1C shows a simulated alternating voltage  $V_o$  for a case where the series resonance frequency of the inductor **102** and the capacitor **103** is set to be equal to the resonance frequency of the vibration member **101**. In this simulation, parameters were set as follows. The self-inductance  $L$  of the inductor **102** was set to 2 mH, the capacitance  $C$  of the capacitor **103** was set to 6.5 nF, the self-inductance  $L_m$  of the equivalent coil **301b** was set to 0.1 H, and the capacitance  $C_m$  of the equivalent capacitor **301c** was set to 130 pF. In FIG. 1C, a vertical axis indicates the gain of the amplitude of the alternating voltage  $V_o$  at the output side relative to the alternating voltage  $V_i$  at the input side. For example, when the gain of the amplitude is equal to 3, if the amplitude of  $V_i$  is 100 V, then the amplitude of  $V_o$  is 300 V. As can be seen from FIG. 1C, by setting  $f_s$  to be equal to  $f_m$ , it is possible to achieve a gradual change in the frequency characteristic of the alternating voltage  $V_o$  in a range close to  $f_m$ . The change in the amplitude of the alternating voltage  $V_o$  in the range close to  $f_m$  is caused by a change in impedance of the self-inductance  $L_m$  and the capacitance  $C_m$  of the mechanically vibrating part of the vibration member **101**. In the present embodiment, this problem is reduced by setting  $f_s$  to be equal to  $f_m$  thereby achieving impedance matching with the impedance of the mechanically vibrating part of the vibration member **101** and thus reducing the change in the amplitude of the alternating voltage  $V_o$ . The reduction in the change in the frequency characteristic of the alternating voltage  $V_o$  in the range close to  $f_m$  leads to a reduction in change of the alternating voltage  $V_o$  due to a variation of a load (equivalent resistor **301d**) or the inductor **102**. This is because the good impedance matching with the mechanically vibrating part of the vibration member **101** is maintained, and thus changes in characteristic of circuit elements do not have a significant influence on the frequency characteristic in the frequency range around  $f_m$ .

Note that the parameters are also set such that an electric resonance of the inductor **102** and the capacitor **103** and the capacitor **301a** of the vibration member **101** causes the amplitude of the alternating voltage  $V_o$  to have a peak at a particular frequency. Hereinafter, the peak frequency of the alternating voltage  $V_o$  is denoted by  $f_e$ . As can be seen in FIG. 1C, by setting  $f_e$  to be higher than  $f_m$ , it is possible to obtain a frequency characteristic with a small voltage change in a frequency range from  $f_m$  to  $f_e$  regardless of a change in the driving frequency  $f_d$  of the vibration member **101**.

First Comparative Example in which Only Inductor is Connected in Series to Vibration Member

Referring to FIG. 2, a discussion is given below for a case where only the inductor **102** is connected in series to the

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vibration member **101**. FIG. 2A illustrates a driving circuit in which only an inductor **102** is connected in series to the vibration member **101**. FIG. 2B shows a simulated frequency characteristic of the alternating voltage  $V_o$  for a case in which the circuit shown in FIG. 2A is used. In the simulation, parameters were set such that the electric resonance of the inductor **102** and the capacitor **301a** of the vibration member **101** caused the amplitude of the alternating voltage  $V_o$  to have a peak at a particular frequency. More specifically, the parameters were set as follows. The self-inductance  $L$  of the inductor **102** was to be 1.23 mH and the intrinsic capacitance  $C_d$  of the capacitor **301a** of the vibration member **101** was set to 3.5 nF such that the alternating voltage  $V_o$  had a peak at a frequency of 76.707 kHz. Furthermore, in the simulation, the resonance frequency  $f_m$  of the vibration member **101** was assumed to be 44.142 kHz. As can be seen from FIG. 2B, the frequency characteristic of the alternating voltage  $V_o$  has a great change in voltage in a frequency range around  $f_m$ , which results in degradation in controllability. Another problem is that a steep change occurs in the alternating voltage  $V_o$  in a range from the resonance frequency  $f_m$  of the vibration member **101** to the peak frequency  $f_e$  of  $V_o$ , and this steep change causes a high voltage to be output in a high range of the driving frequency. Therefore, circuit elements such as a switching element used in the driving circuit need to have a high withstand voltage, which causes an increase in cost. Furthermore, this leads to an increase in the alternating voltage  $V_o$  due to a variation of the load (equivalent resistor **301d**) or the inductor **102**.

Maximum Allowable Difference Between  $f_s$  and  $f_m$

In the present embodiment of the invention, the series resonance frequency  $f_s$  of the inductor **102** and the capacitor **103** connected in series to the vibration member **101** does not need to be exactly equal to the resonance frequency  $f_m$  of the vibration member **101**. That is, it is possible to achieve a gradual change in the frequency characteristic of the alternating voltage  $V_o$  in a frequency range around  $f_m$  as long as the difference between  $f_s$  and  $f_m$  is within a particular narrow range, although the smaller the difference is between  $f_s$  and  $f_m$ , the better result is obtained.

To determine a range of  $f_s$  in which the advantages of the present embodiment of the invention are achieved, an investigation is made on an effect of a change in phase of the alternating voltage  $V_o$  in a frequency range around the resonance frequency  $f_m$  of the vibration member **101**. FIG. 3A shows a result of simulation in terms of the phase of the alternating voltage  $V_o$  where a horizontal axis indicates the frequency, and a change in phase of  $V_o$  is shown for a range from 40 kHz to 48 kHz around a resonance frequency  $f_m$  set to be equal to 44.142 kHz. The simulation was performed for the driving circuit shown in FIG. 1A. In the simulation, the series resonance frequency  $f_s$  of the inductor **102** and the capacitor **103** was varied in a range from 0.73 to 1.2 in relative value with respect to  $f_m$  (i.e.,  $f_s/f_m$ ), and the result is plotted in FIG. 3A. Note that when  $f_s/f_m$  was varied,  $L$  and  $C$  were adjusted so that the peak frequency  $f_e$  was maintained at 61.798 kHz ( $=1.4 \cdot f_m$ ). The reason why the peak frequency  $f_e$  was maintained at the constant value is that a change in the value of the peak frequency  $f_e$  causes a great change in the amplitude of  $V_o$  in a frequency range around the resonance frequency  $f_m$  of the vibration member **101**. For the purpose of comparison, the simulation was also performed for the circuit according to the conventional technique shown in FIG. 2A, and a result was plotted. In the simulation for the circuit shown in FIG. 2A, the self-inductance  $L$  of the inductor **102** was set to 1.97 mH, and the peak frequency  $f_e$  of the alternating voltage  $V_o$  was set to be 61.798 kHz ( $=1.4 \cdot f_m$ ).



From FIG. 3A, it can be seen that the conventional circuit configuration has a great phase delay. The maximum phase delay almost reaches 60°. In contrast, when  $f_s$  was set such that  $f_s/f_m=1$ ,  $V_o$  had substantially no phase change. When  $f_s/f_m=1$ , the self-inductance  $L$  of the inductor **102** was 4.17 mH and the capacitance  $C$  of the capacitor **103** was 3.12 nF. Generally, the phase change increases in a negative direction with decreasing  $f_s/f_m<1$ , while the phase change increases in a positive direction with increasing  $f_s/f_m>1$ .

A simulation was also performed in terms of a dependency of the alternating voltage  $V_o$  on the frequency to detect a relationship between the phase change of the alternating voltage  $V_o$  shown in FIG. 3A and a change of the amplitude of the alternating voltage  $V_o$ . The result is shown in FIG. 3B. The simulation was performed under the same condition as that of FIG. 3A. The change of the alternating voltage  $V_o$  was calculated for values of  $f_s/f_m$  from 0.73 to 1.2, and the result was plotted. For the purpose of comparison, the change of the alternating voltage  $V_o$  for the conventional circuit configuration was also calculated and the result was plotted. As can be seen, the phase change shown in FIG. 3B roughly corresponds to the voltage change shown in FIG. 3A. That is, the change in the amplitude of  $V_o$  increases with increase change in phase of  $V_o$ .

FIG. 4 illustrates a simulation result in terms of a relative change in phase with respect to a change that occurs in the conventional configuration as a function of  $f_s/f_m$ . In FIG. 4, a horizontal axis represents  $f_s/f_m$ , i.e., the ratio of  $f_s$  to the resonance frequency  $f_m$  of the vibration member **101**. A vertical axis represents the ratio of the change in phase to the change in phase that occurs in the conventional configuration. The ratio of the change in phase was calculated as follows. First, the absolute value of the change in phase of  $V_o$  that occurs in the conventional configuration was calculated for a frequency range from 40 kHz to 48 kHz, and a maximum value was detected. Hereinafter, the detected maximum value is referred to as the maximum phase change in the conventional configuration. Next, for the configuration shown in FIG. 1A, the absolute value of the phase change of  $V_o$  was calculated as a function of  $f_s/f_m$  for a frequency range from 40 kHz to 48 kHz, and a maximum value was detected. Hereinafter, the detected maximum value is referred to as the maximum phase change depending on  $f_s/f_m$ . The ratio of the maximum phase change depending on  $f_s/f_m$  to the maximum phase change in the conventional configuration was then calculated, and the result is plotted such that the ratio is represented by the vertical axis.

In the present embodiment of the invention, as shown in FIG. 4, when the relative phase change with respect to the phase change of the conventional circuit configuration is defined is smaller than a threshold value set to 0.5, the frequency characteristic of the alternating voltage  $V_o$  can be regarded as having a sufficiently small change in a frequency range around  $f_m$ . Such a small change can be achieved when  $f_s/f_m$  is within a range shown below.

$$0.73 \cdot f_m < f_s < 1.2 \cdot f_m$$

The above result was obtained when parameters were set as follows. The peak frequency  $f_e$  was set to 61.798 kHz ( $=1.4 \cdot f_m$ ), and the intrinsic capacitance  $C_d$  of the capacitor **301a** of the vibration member **101** was set to 3.5 nF. Note that a similar result is obtained for various values of the peak frequency  $f_e$  and for various values of the intrinsic capacitance  $C_d$ . In the simulation, other parameters were set as follows. The self-inductance  $L_m$  of the equivalent coil **301b** of the vibration member **101** was set to 0.1 H, the capacitance

$C_m$  of the equivalent capacitor **301c** was set to 130 pF, and the resistance  $R_m$  of the equivalent resistor **301d** was set to 1 k $\Omega$ .

Thus, by setting  $f_s$  within the range described above to reduce the phase change of the alternating voltage  $V_o$  to a level less than one half of that of the conventional configuration, it also becomes possible to reduce the change in  $V_o$  to a level less than one of that of the conventional configuration. That is, even when  $f_s$  is not exactly equal to  $f_m$ , if  $f_s$  and  $f_m$  satisfy the above-described relationship, it is possible to reduce the change in frequency characteristic of the alternating voltage  $V_o$  in the range around  $f_m$  compared with the conventional circuit configuration. Thus, it is possible to achieve a stable control characteristic due to a synergy effect of the reduction in the change in the alternating voltage  $V_o$  and the improvement in phase delay.

FIG. 5 shows a result of simulation in terms of the frequency characteristic of the alternating voltage  $V_o$  for a case where the relationship between  $f_s$  and  $f_m$  satisfies the above condition (and more specifically, the series resonance frequency  $f_s$  is lower than the resonance frequency  $f_m$  of the vibration member **101**). The simulation was performed for the circuit configuration shown in FIG. 1A. As shown in FIG. 5, the change in the alternating voltage  $V_o$  in a range near the resonance frequency  $f_m$  is smaller than that shown in FIG. 2B. Note that, in the simulation, the resonance frequency of the vibration member **101** was assumed to be 44.142 kHz, and the capacitance of the capacitor **103** was intentionally increased by 10% so that the series resonance frequency  $f_s$  was set to  $0.95 \cdot f_m$ , i.e., 42.087 kHz which is smaller by about 2 kHz than  $f_m$ . As can be seen from the simulation result, even when  $f_s$  is not exactly equal to  $f_m$ , it is possible to reduce the change in the alternating voltage  $V_o$  in an frequency range around the resonance frequency  $f_m$ .

Determination of Inductance  $L$  of Inductor **102** and Capacitance  $C$  of Capacitor **103**

Next, a method of determining the capacitance of the capacitor **103** and the inductance of the inductor **102** is described below. The series resonance frequency  $f_s$  is given by the product of the inductance  $L$  of the inductor **102** and the capacitance  $C$  of the capacitor **103**. Therefore, for a given value of  $f_s$ , there can be an infinite number of combinations of inductance  $L$  and the capacitance  $C$  that satisfy the give value of  $f_s$ . However, if the peak frequency  $f_e$  of the alternating voltage  $V_o$  is first determined, there is only one combination of inductance  $L$  and capacitance  $C$  for the given  $f_s$ .

The peak frequency  $f_e$  of  $V_o$  can be calculated from the inductance  $L$  of the inductor **102**, the capacitance  $C$  of the capacitor **103**, and the intrinsic capacitance  $C_d$  of the capacitor **301a** of the vibration member **101** according to equation (1-3) shown below.

$$f_e = 1 / \left( 2\pi \sqrt{L \cdot \frac{C \cdot C_d'}{C + C_d'}} \right) \quad (1-3)$$

In practical calculation of the peak frequency  $f_e$ , the vibration member **101** may be regarded as an equivalent capacitor, and its capacitance may be determined taking into account an effect of the RLC series circuit of the mechanically vibrating part. Hereinafter, the resultant capacitance is denoted by  $C_d'$ . For example, when the effect of the RLC series circuit of the mechanically vibrating part provides an equivalent capacitance change of 134 pF,  $C_d'$  may be determined as follows.

$$C_d' = C_d - 134 \text{ pF}$$



By determining the value of the peak frequency  $f_e$  according to equation (1-3), it is possible to determine a relationship between  $L$  and  $C$ . FIG. 6 shows the relationship between the inductance  $L$  of the inductor **102** and the capacitance  $C$  of the capacitor **103** for some values of the peak frequency  $f_e$ . A horizontal axis indicates the value of  $C$  and a vertical axis indicates the value of  $L$ . In FIG. 6, values of  $L$  and  $C$  determined according to equation (1-3) are plotted for three values of  $f_e$ , i.e.,  $f_e=1.4 \cdot f_m$ ,  $f_e=1.5 \cdot f_m$ , and  $f_e=2 \cdot f_m$ . In FIG. 6, values of  $L$  and  $C$  are also plotted for a case where the product  $L$  and  $C$  is given by  $L_m C_m$ , i.e., for a case where the series resonance frequency  $f_s$  is equal to  $f_m$ . As described above,  $L_m$  is the self-inductance of the equivalent coil **301b**, and  $C_m$  is the capacitance of the equivalent capacitor **301c**. As shown in FIG. 6, for a particular constant value of  $f_e$ , each curve representing inductance as a function of capacitance intersects the line of  $LC=L_m C_m$  at one point. Each intersection gives optimum values of inductance  $L$  and capacitance  $C$  for a case where  $f_s$  equals  $f_m$ . For example, if  $f_e=1.4 \cdot f_m$ , then  $L$  is 4.17 mH and  $C$  is 3.12 nF.

The value of  $f_e$  is discussed in further detail below. In the present embodiment of the invention, when the driving frequency of the vibration member **101** is  $f_d$ , the peak frequency  $f_e$  may be set so as to satisfy a condition  $f_e < 1.5 \cdot f_d$ . The reason for this is described below.

FIG. 7 shows a frequency characteristic of the alternating voltage  $V_o$  for a case where  $f_e < 1.5 \cdot f_d$ . In FIG. 7,  $2 \cdot f_d$  is a second order harmonic frequency of the driving frequency  $f_d$ . It may be better for the alternating voltage  $V_o$  to have a waveform similar to a sine wave having as low harmonic components such as second-order or third-order harmonic components as possible. In practice, the driving waveform of alternating voltage  $V_o$  has a pulse duty that is not exactly equal to 50%, and thus it may be better to reduce the second-order harmonic component. For the above reason, by setting the peak frequency  $f_e$  to a value lower than  $1.5 \cdot f_d$ , it is possible to reduce the amplitude of the second-order harmonic component of the alternating voltage  $V_o$  at the frequency of  $2 \cdot f_d$  to a level smaller than that at the driving frequency  $f_d$ . For example, when the driving frequency  $f_d$  is 46 kHz,  $1.5 \cdot f_d$  is 69 kHz. In this case, if the inductance  $L$  of the inductor **102** is set to be 4 mH, and the capacitance  $C$  of the capacitor **103** is set to be 3.25 nF, then the peak frequency  $f_e$  is 61.3 kHz and thus the above-described condition is satisfied.

#### Modification of First Embodiment

FIG. 8 illustrates a driving circuit configured to drive a vibration-type actuator according to a modification of the first embodiment of the present invention. In this configuration, an inductor **201** for parallel resonance is connected in parallel to the vibration member **101**. The provision of the inductor **201** for parallel resonance causes parallel resonance to occur with the capacitor **301a** (the intrinsic capacitance  $C_d$ ) of the vibration member **101**. This makes it possible to achieve a further reduction in the change in the alternating voltage  $V_o$  due to a variation of the load (equivalent resistor **301d**) or the inductor **102**. Note that in the present modification,  $f_s$  may be determined from equation (1-1) described above.

#### Second Embodiment

Next, with reference to FIGS. 9A and 9B, a second embodiment of the present invention is described below. The second embodiment is different from the first embodiment described above in that voltage step-up is performed using a transformer.

FIG. 9A illustrates a driving circuit configured to drive a vibration-type actuator according to the second embodiment of the present invention. In this configuration of the driving circuit, a secondary coil **401b** of a transformer **401** is connected in parallel to the vibration member **101** (i.e., the secondary coil **401b** of the transformer **401** is connected in parallel to the electro-mechanical energy conversion element), and a capacitor **103** is connected in series to a primary coil **401a** of the transformer **401**. A capacitance element such as a film capacitor may be used as the capacitor **103**. By reducing the coupling of the transformer **401**, it is possible to increase the leakage inductance of the primary coil **401a** of the transformer **401** and the leakage inductance of the secondary coil **401b** of the transformer **401**. These leakage inductances can be employed as the inductor. The leakage inductances are equivalently represented by an inductor **102a** (leakage inductance of the primary coil **401a** of the transformer **401**) and an inductor **102b** (leakage inductance of the secondary coil **401b** of the transformer **401**). A series resonance circuit is formed by these two leakage inductances and the capacitor **103**. Although the capacitor **103** is connected to a lower terminal of the primary coil **401a** of the transformer **401** in the configuration shown in FIG. 9A, the capacitor **103** may be connected to an upper terminal of the primary coil **401a**. The series resonance frequency of the leakage inductance **102a** of the primary coil **401a**, the leakage inductance **102b** of the secondary coil **401b**, and the capacitor **103** is denoted by  $f_s$ , and the resonance frequency of the vibration member **101** is denoted by  $f_m$ . If the leakage inductance **102a** of the primary coil **401a** of the transformer **401** is denoted by  $L_1$ , the leakage inductance **102b** of the secondary coil **401b** of the transformer **401** is denoted by  $L_2$ , and the turn ratio of the secondary coil **401b** to the primary coil **401a** is denoted by  $N$ , and the capacitance of the capacitor **103** is denoted by  $C$ , then

$$f_s = 1 / (2\pi \sqrt{\{L_1 + (L_2/N^2)\}C}) \quad (2-1)$$

$$f_m = 1 / (2\pi \sqrt{L_m C_m}) \quad (2-2)$$

As described above,  $L_m$  and  $C_m$  are equivalent circuit constants associated with the mechanical vibration of the vibration member **101**, where  $L_m$  is the self-inductance of the equivalent coil **301b** and  $C_m$  is the capacitance of the equivalent capacitor **301c**.

FIG. 9B is a diagram illustrating a simulation result in terms of a frequency characteristic of the alternating voltage  $V_o$  for a case where the series resonance frequency  $f_s$  is set to be equal to the resonance frequency  $f_m$  of the vibration member **101**. As can be seen from FIG. 9B, as in the first embodiment, by setting  $f_s$  to be equal to  $f_m$ , it is possible to achieve a gradual change in the frequency characteristic of the alternating voltage  $V_o$  in a range around  $f_m$ . In the simulation,  $L$  was set to 20  $\mu$ H ( $=L_1 + L_2/N^2$ ),  $C$  to 650 nF,  $L_m$  to 0.1 H,  $C_m$  to 130 pF, and the turn ratio  $N$  to 10. The reduction in the change in the frequency characteristic of the alternating voltage  $V_o$  in the range close to  $f_m$  leads to a reduction in change of the alternating voltage  $V_o$  due to a variation of a load (equivalent resistor **301d**) or the inductor **102**. Hereinafter, the peak frequency of the alternating voltage  $V_o$  is denoted by  $f_e$ . By setting  $f_e$  to be higher than  $f_m$  as shown in FIG. 9B, it is possible to obtain a frequency characteristic with a small voltage change in a frequency range from  $f_m$  to  $f_e$  regardless of a change in the driving frequency  $f_d$ . However, in the case where the transformer is used, the connection of the inductor **102** and the capacitor **103** causes the alternating voltage  $V_o$  to have another peak at a frequency lower than the resonance frequency  $f_m$  of the vibration member **101**. That is, the alter-



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nating voltage  $V_o$  has two peaks at frequencies higher and lower than  $f_m$ . In the present embodiment,  $f_e$  denotes the higher peak.

As in the first embodiment, the series resonance frequency  $f_s$  may not be exactly equal to the resonance frequency  $f_m$  of the vibration member **101**. The advantages described above may be achieved by setting the series resonance frequency  $f_s$  within a range around  $f_m$  so as to satisfy a condition shown below.

$$0.73 \cdot f_m < f_s < 1.2 \cdot f_m$$

By setting  $f_s$  within the above-described range, it is possible to achieve a stable control characteristic due to a synergy effect of the reduction in the change in the alternating voltage  $V_o$  and an improvement in phase delay.

In the case where the transformer is used, a coefficient associated with LC in the formula used in calculation of  $f_s$  varies depending on whether the inductor **102** and the capacitor **103** are connected to the primary coil or the secondary coil. Thus, there are four configurations as described below.

(1) L and C are connected to the primary side of the transformer.

(2) L and C are connected to the secondary side of the transformer.

(3) L is connected to the primary coil of the transformer and C is connected to the secondary coil of the transformer.

(4) C is connected to the primary coil of the transformer and L is connected to the secondary coil of the transformer.

In the configurations (1) and (2) described above, the coefficient of LC is equal to 1. On the other hand, in the configuration of (3), the coefficient is  $N^2$ , i.e., the term including LC is given by  $N^2 \cdot LC$ . This is because L located on the primary side is equivalent to  $N^2 \cdot L$  on the secondary side where N is the turn ratio of the transformer. In the configuration (4), the coefficient is  $1/N^2$ , i.e., the term including LC is given by  $(1/N^2) \cdot LC$ . This is because C located on the primary side is equivalent to  $(1/N^2) \cdot C$  on the secondary side where N is the turn ratio of the transformer.

Next, FIG. 10 B is a diagram illustrating a simulation result in terms of a frequency characteristic of the alternating voltage  $V_o$  for a case where the series resonance frequency  $f_s$  is lower than the resonance frequency  $f_m$  of the vibration member **101**. This simulation was performed for a circuit configuration shown in FIG. 10A. The resonance frequency of the vibration member **101** was assumed to be 44.142 kHz. The capacitance of the capacitor **103** was intentionally increased by 10% so that the series resonance frequency  $f_s$  was set to  $0.95 \cdot f_m$ , i.e., 42.087 kHz which is smaller by about 2 kHz than  $f_m$ . As can be seen from FIG. 10B, even when  $f_s$  is not exactly equal to  $f_m$ , it is possible to reduce the change in the alternating voltage  $V_o$  in an frequency range around the resonance frequency  $f_m$ .

The capacitance of the capacitor **103** and the inductance of the inductor **102** may be determined in a similar manner to the first embodiment. That is, if the peak frequency  $f_e$  of the alternating voltage  $V_o$  is first determined, then it is possible to uniquely determine a combination of the inductance and the capacitance.

As in the first embodiment, when the driving frequency of the vibration member **101** is denoted by  $f_d$ , the peak frequency  $f_e$  is set such that a condition shown below is satisfied.

$$f_e < 1.5 \cdot f_d$$

By setting the peak frequency  $f_e$  so as to satisfy the above condition, it is possible to reduce the second-order harmonic component as described above with reference to FIG. 7. For example, when the driving frequency  $f_d$  is 46 kHz,  $1.5 \cdot f_d$  is 69

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kHz. In this case, in the circuit shown in FIG. 5, if the inductance L of the inductor **102** is set to be 40  $\mu\text{H}$ , and the capacitance C of the capacitor **103** is set to be 0.325  $\mu\text{F}$ , then the peak frequency  $f_e$  is 61.3 kHz and thus the above-described condition is satisfied.

## First Modification of Second Embodiment

FIG. 10A illustrates a driving circuit configured to drive a vibration-type actuator according to a first modification of the second embodiment of the present invention. In this configuration of the driving circuit, a secondary coil **401b** of a transformer **401** is connected in parallel to the vibration member **101**, and an inductor **102** and a capacitor **103** are connected in series to a primary coil **401a** of the transformer **401**. Note that the circuit configuration in terms of the inductor **102** and the capacitor **103** is not limited to that shown in FIG. 10A as long as the inductor **102** and the capacitor **103** are connected in series to the primary coil **401a** of the transformer **401**. When the inductor **102** is located on the primary side of the transformer **401**, the inductance thereof may be as small as  $1/N^2$  times the inductance which would be necessary when the inductor **102** is located on the secondary side. Note that N denotes the turn ratio. When the capacitor **103** is located on the primary side of the transformer **401**, the withstand voltage of the capacitor **103** may be as small as  $1/N$  times the withstand voltage which would be necessary when the capacitor **103** is located on the secondary side.

If the inductance of the inductor **102** is denoted by L and the capacitance of the capacitor **103** is denoted by C, the series resonance frequency  $f_s$  is given by equation (2-3) shown below, which is the same as equation (1-1) described above.

$$f_s = 1 / (2\pi\sqrt{LC}) \quad (2-3)$$

By setting the series resonance frequency  $f_s$  determined according equation (2-3) so as to be equal to the resonance frequency  $f_m$  of the vibration member **101**, it is possible to achieve a gradual change in the frequency characteristic of the alternating voltage  $V_o$  in a range around  $f_m$ . The reduction in the change in the frequency characteristic of the alternating voltage  $V_o$  in the range close to  $f_m$  leads to a reduction in change of the alternating voltage  $V_o$  due to a variation of a load (equivalent resistor **301d** of the mechanical vibration of the vibration member **101**) or the inductor **102**. FIGS. 11A and 11B illustrate effects of the reduction in change in the alternating voltage  $V_o$ . FIGS. 11A and 11B show simulation result in terms of change in the alternating voltage  $V_o$  due to variations of a load and the inductance of the inductor **102** for the circuit shown in FIG. 10A. More specifically, FIG. 11A illustrates a simulation result in terms of a change in the alternating voltage  $V_o$  due to a variation of the load. In FIG. 11A, to provide a better understanding about the change around the resonance frequency  $f_m$  of the vibration member **101**, the result is shown only for a frequency range from 40 kHz to 50 kHz in a horizontal axis. The calculation was performed for three different values of the load, i.e., a reference value and the reference value  $\pm 20\%$ . This variation of the load was assumed to appear as a change in the equivalent resistance  $R_m$  in the equivalent circuit of the vibration member **101**. The result shown in FIG. 11A indicates that the variations of the load have substantially no effect on the alternating voltage  $V_o$ , thus high controllability can be achieved.

FIG. 11B shows a simulation result in terms of a change in the alternating voltage  $V_o$  due to a variation of the inductance of the inductor **102**. The calculation was performed for three different values of the inductance of the inductor **102**, i.e., a



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reference value and the reference value  $\pm 20\%$ . The result shown in FIG. 11B indicates the variation of the inductance of the inductor **102** does not have a significant influence on the alternating voltage  $V_o$ . That is, when the driving circuit has two or more phases, the variation of the inductance of the inductor **102** does not have a significant influence, and thus it is possible to reduce unevenness in the travelling wave.

In the present embodiment, the transformer **401** may have leakage inductance. In this case, it is necessary to take into account the effect of the leakage inductance in the calculation of the series resonance frequency  $f_s$  substantially equal to the resonance frequency  $f_m$  of the vibration member **101**.

## Second Modification of Second Embodiment

FIG. 12A illustrates a driving circuit configured to drive a vibration-type actuator according to a second modification of the second embodiment of the present invention. In this configuration of the driving circuit, a secondary coil **401b** of a transformer **401** is connected in parallel to the vibration member **101**, a capacitor **103** is connected in series to a primary coil **401a** of the transformer **401**, and an inductor **102** is connected in series to the secondary coil **401b** of the transformer **401**. When the inductor **102** is located on the secondary side of the transformer **401**, the maximum allowable current of the inductor **102** may be as small as  $1/N$  of the maximum allowable current that would be necessary when the inductor **102** is located on the primary side of the transformer **401**. Note that  $N$  denotes the turn ratio. If the inductance of the inductor **102** is  $L$ , and the capacitance of the capacitor **103** is  $C$ , then the series resonance frequency  $f_s$  is given by equation (2-4) shown below.

$$f_s = 1 / (2\pi \sqrt{LC/N^2}) \quad (2-4)$$

By setting the series resonance frequency  $f_s$  determined according equation (2-4) so as to be equal to the resonance frequency  $f_m$  of the vibration member **101**, it is possible to achieve a gradual change in the frequency characteristic of the alternating voltage  $V_o$  in a range around  $f_m$ , and it is also possible to reduce the change in the alternating voltage  $V_o$  due to the variation of the load (equivalent resistor **301d**) or the inductance of the inductor **102**.

## Third Modification of Second Embodiment

FIG. 12B illustrates a driving circuit configured to drive a vibration-type actuator according to a third modification of the second embodiment of the present invention. In this configuration of the driving circuit, a secondary coil **401b** of a transformer **401** is connected in parallel to the vibration member **101**, an inductor **102** is connected in series to a primary coil **401a** of the transformer **401**, and a capacitor **103** is connected in series to the secondary coil **401b** of the transformer **401**. When the inductor **102** is located on the primary side of the transformer **401**, the inductance thereof may be as small as  $1/N^2$  of the inductance which would be necessary when the inductor **102** is located on the secondary side. When the capacitor **103** is located on the secondary side of the transformer **401**, the capacitance thereof may be as small as  $1/N^2$  of the capacitance which would be necessary when the capacitor **103** is located on the primary side. In this configuration, the series resonance frequency  $f_s$  is given by equation (2-5) shown below.

$$f_s = 1 / (2\pi \sqrt{LC \cdot N^2}) \quad (2-5)$$

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The series resonance frequency  $f_s$  determined according equation (2-5) is set to be equal to the resonance frequency  $f_m$  of the vibration member **101**.

## Fourth Modification of Second Embodiment

FIG. 12C illustrates a driving circuit configured to drive a vibration-type actuator according to a fourth modification of the second embodiment of the present invention. In this configuration of the driving circuit, a secondary coil **401b** of a transformer **401** is connected in parallel to the vibration member **101**, and an inductor **102** and a capacitor **103** are connected in series to a secondary coil **401b** of the transformer **401**. When the inductor **102** is located on the secondary side of the transformer **401**, the maximum allowable current of the inductor **102** may be as small as  $1/N$  of the maximum allowable current that would be necessary when the inductor **102** is located on the primary side of the transformer **401**. When the capacitor **103** is located on the secondary side of the transformer **401**, the capacitance thereof may be as small as  $1/N^2$  of the capacitance which would be necessary when the capacitor **103** is located on the primary side. In this configuration, the series resonance frequency  $f_s$  is given by equation (2-6) shown below.

$$f_s = 1 / (2\pi \sqrt{LC}) \quad (2-6)$$

The series resonance frequency  $f_s$  determined according equation (2-6) is set to be equal to the resonance frequency  $f_m$  of the vibration member **101**.

## Fifth Modification of Second Embodiment

FIG. 12D illustrates a driving circuit configured to drive a vibration-type actuator according to a fifth modification of the second embodiment of the present invention. In this configuration, a resistor **2801** is connected in parallel to a primary coil **401a** of a transformer **401**. As described above, when a transformer is used as in the second embodiment and first to fourth modifications thereof, the connection of the inductor **102** and the capacitor **103** causes the alternating voltage  $V_o$  to have two peaks at frequencies higher and lower than  $f_m$ . In the present modification, the provision of the resistor **2801** leads to a reduction in the peak at the lower frequency. The reduction in the peak at the lower frequency makes it possible to reduce an influence of disturbance in a low frequency range and an influence of a variation of the load.

## Sixth Modification of Second Embodiment

FIG. 12E illustrates a driving circuit configured to drive a vibration-type actuator according to a sixth modification of the second embodiment of the present invention. In this sixth modification, a resistor **2801** and an inductor **2901** for parallel resonance are connected in parallel to a primary coil **401a** of a transformer. In this sixth modification, the inductor **2901** for parallel resonance provides a more effective reduction in the peak in the low frequency range. Note that in the present modification,  $f_s$  can be determined according to equation (2-5) described above.

Second Comparative Example in which Only an Inductance is Connected in Series to a Vibration Member

Next, with reference to FIGS. 13A and 13B, a comparative example of a configuration is described in which a transformer is used and only an inductor **102** is connected in series to the vibration member **101**. FIG. 13A illustrates a conventional driving circuit using a transformer for driving a vibration-type actuator. In this circuit configuration, an inductor



**102** is connected in series to a secondary coil of the transformer **401**. FIG. **13B** shows a simulation result in terms of a frequency characteristic of an alternating voltage  $V_o$  output from the secondary side of the transformer **401** in the circuit shown in FIG. **13A**. In the simulation, the inductance  $L$  of the inductor **102** was set to be 1.23 mH, the alternating voltage  $V_o$  was assumed to have a peak at a frequency of 76.707 kHz, and the resonance frequency of the vibration member **101** was assumed to be 44.142 kHz. As shown in FIG. **13B**, the frequency characteristic of the alternating voltage  $V_o$  has a great change in voltage around  $f_m$ , which leads to a reduction in controllability. A steep change occurs in the alternating voltage  $V_o$  in a range from the resonance frequency  $f_m$  of the vibration member **101** to the peak frequency  $f_e$  of  $V_o$ , and this steep change causes a high voltage to be output in a high range of the driving frequency. Therefore, circuit elements such as a switching element used in the driving circuit need to have a high withstand voltage, which causes an increase in cost.

FIGS. **14A** and **14B** show simulation result in terms of change in the alternating voltage  $V_o$  due to variations of a load (equivalent resistor **301d**) and the inductance of the inductor **102** for the circuit shown in FIG. **13A**.

More specifically, FIG. **14A** illustrates a simulation result in terms of a change in the alternating voltage  $V_o$  due to a variation of the load. To show more clearly the change in the alternating voltage  $V_o$  around the resonance frequency of the vibration member **101**, the result is shown only for a frequency range from 40 kHz to 50 kHz in a horizontal axis. The calculation was performed for three values of the load, i.e., a reference value and the reference value  $\pm 20\%$ . This variation of the load was assumed to appear as a change in the equivalent resistance of the mechanical vibration in the equivalent circuit of the vibration member **101**. The result shown in FIG. **14A** indicates that the variation of the load causes a great change in the frequency characteristic of the alternating voltage  $V_o$ , which results in degradation in controllability.

FIG. **14B** shows a simulation result in terms of a change in the alternating voltage  $V_o$  due to a variation of the inductance of the inductor **102**. It was assumed that a coil was used as the inductor **102** and the calculation was performed for three different values of the inductance of the inductor **102**, i.e., a reference value and the reference value  $\pm 20\%$ . As shown in FIG. **14B**, the variation of the inductance of the inductor **102** causes a great change in the frequency characteristic of the alternating voltage  $V_o$ . Therefore, when the driving circuit has two or more phases, if the inductance of the coil is different among the phases, the amplitude of the alternating voltage  $V_o$  output from the driving circuit becomes different between the phases. That is, alternating voltages  $V_o$  with different amplitudes are applied at the same time to the respective driving electrodes **101a** and **101b** of the vibration member **101** shown in FIG. **16**, which causes unevenness in the travelling wave.

Third Comparative Example in which the Series Resonance Frequency of Capacitor **103** and Primary Coil **401a** of Transformer is Set to be Equal to  $F_m$ .

FIG. **15** shows a simulation result in terms of a frequency characteristic of an alternating voltage  $V_o$  output from a secondary coil of a transformer **401** for a case where the series resonance frequency of a capacitor **103** and a primary coil **401a** of the transformer **401** is set to be equal to the resonance frequency  $f_m$  of the vibration member **101**. The simulation was performed for a circuit configuration shown in FIG. **16**. The transformer **401** was assumed to have an ideal coupling (with a coupling coefficient of 1) with no leakage inductance. Furthermore, it was also assumed that the inductance of the primary coil **401a** of the transformer **401** was 150  $\mu$ H and the

inductance of the secondary coil **401b** of the transformer **401** was 15 mH. The capacitance of the capacitor **103** connected to the primary coil **401a** of the transformer **401** was set to 86.7 nF, and the inductance of the inductor **102** connected to the secondary coil **401b** of the transformer **401** was set to 1 mH. The resonance frequency  $f_m$  of the vibration member **101** was assumed to be 44.142 kHz. Note that the series resonance frequency of the capacitor **103** and the inductor **102** is 170.96 kHz which is greatly different from  $f_m$ . The peak frequency  $f_e$  of the alternating voltage  $V_o$  was 190.927 kHz.

The simulation result shown in FIG. **15** indicates that the frequency characteristic of the alternating voltage  $V_o$  has a great voltage change around  $f_m$ . The simulation also has revealed that the alternating voltage  $V_o$  has a great change in phase in a frequency range around  $f_m$ . That is, Japanese Patent Publication No. 5016277 discloses only the series resonance of the capacitor **103** and the primary coil **401a** of the transformer, but Japanese Patent Publication No. 5016277 does not disclose the technique to adjust the series resonance frequency of the capacitor **103** and the inductor **102**. Thus, in the technique disclosed in Japanese Patent Publication No. 5016277, a great change can occur in the alternating voltage  $V_o$  in a frequency range around  $f_m$ . Furthermore, the steep change in the alternating voltage  $V_o$  in a range from the resonance frequency  $f_m$  of the vibration member **101** to the peak frequency  $f_e$  of  $V_o$  can cause a high voltage to be output in a high range of the driving frequency. Therefore, circuit elements such as a switching element used in the driving circuit need to have a high withstand voltage, which causes an increase in cost. Furthermore, this leads to an increase in the alternating voltage  $V_o$  due to a variation of the load (equivalent resistor **301d**) or the inductor **102**.

Note that the circuit configuration shown in FIG. **16** may be used in the present invention. In this circuit configuration shown in FIG. **16**, by setting  $f_s$  such that  $0.73 \cdot f_m < f_s < 1.2 \cdot f_m$ , it is possible to achieve a gradual change in the frequency characteristic of the alternating voltage  $V_o$  in a range around  $f_m$ .

While the present invention has been described with reference to exemplary embodiments, it is to be understood that the invention is not limited to the disclosed exemplary embodiments. The scope of the following claims is to be accorded the broadest interpretation so as to encompass all such modifications and equivalent structures and functions.

What is claimed is:

1. A driving circuit configured to drive a vibration member comprising an electro-mechanical energy conversion element, the driving circuit comprising:

a transformer connected to the electro-mechanical energy conversion element and comprising:

a primary coil configured such that an alternating voltage is applied to the primary coil; and

a secondary coil connected to the electro-mechanical energy conversion element; and

an inductor connected to the primary coil in series, wherein parameters of the driving circuit are set such that, when a frequency of a peak voltage applied to the electro-mechanical energy conversion element is denoted by  $f_e$  and a driving frequency of the vibration member is denoted by  $f_d$ , a condition  $f_e < 1.5 \cdot f_d$  is satisfied.

2. The driving circuit according to claim 1, wherein the inductor is a leakage inductance of the transformer.

3. The driving circuit according to claim 1, wherein the vibration member is configured to generate a vibration wave in response to the alternating voltage applied to the electro-mechanical energy conversion element.



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4. The driving circuit according to claim 3, wherein the vibration member is configured to relatively move a moving member in response to the vibration wave.

5. The driving circuit according to claim 1, further comprising a resistor connected to the electro-mechanical energy conversion element in parallel.

6. The driving circuit according to claim 1, further comprising a resistor and an inductor connected to the electro-mechanical energy conversion element in parallel.

7. The driving circuit according to claim 1, wherein, when a resonance frequency of the driving member is denoted  $f_m$ , a condition  $f_m < f_e$  is satisfied.

8. An apparatus comprising:

a vibration member including an electro-mechanical energy conversion element; and

a driving circuit comprising:

a transformer connected to the electro-mechanical energy conversion element and comprising:

a primary coil configured such that an alternating voltage is applied to the primary coil; and

a secondary coil connected to the electro-mechanical energy conversion element; and

an inductor connected to the primary coil in series, wherein parameters of the driving circuit are set such that, when a frequency of a peak voltage applied to the elec-

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tro-mechanical energy conversion element is denoted by  $f_e$  and a driving frequency of the vibration member is denoted by  $f_d$ , a condition  $f_e < 1.5 \cdot f_d$  is satisfied.

9. The apparatus according to claim 8, wherein the inductor is a leakage inductance of the transformer.

10. The apparatus according to claim 8, wherein the vibration member is configured to generate a vibration wave in response to the alternating voltage applied to the electro-mechanical energy conversion element.

11. The apparatus according to claim 8, further comprising a resistor connected to the electro-mechanical energy conversion element in parallel.

12. The apparatus according to claim 8, further comprising a resistor and an inductor connected to the electro-mechanical energy conversion element in parallel.

13. The apparatus according to claim 8, wherein, when a resonance frequency of the driving member is denoted  $f_m$ , a condition  $f_m < f_e$  is satisfied.

14. The apparatus according to claim 8, further comprising a moving member configured to move relative to the vibration member.

15. The apparatus according to claim 14, wherein the moving member is configured to move in response to a vibration wave relative to the vibration member.

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